

IMPROVED CONVERGENCE IN  
TRAFFIC ACCIDENT SIMULATION  
USING EXPERT SYSTEMS TECHNIQUES

By

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## TABLE OF CONTENTS

	<u>page</u>
ACKNOWLEDGMENTS .....	ii
LIST OF TABLES .....	v
LIST OF FIGURES .....	vi
ABSTRACT .....	viii
 CHAPTERS	
1. INTRODUCTION .....	1
Statement of the Problem .....	1
Objectives, Study Scope and Limits .....	5
2. LITERATURE REVIEW .....	8
Accident Reconstruction Overview .....	8
Data Needed in Accident Reconstruction .....	10
Systematic Procedure .....	11
Computer Programs for Accident Reconstruction .....	19
Sensitivity of Selected Variables in EDSMAC and	
Converging Procedure .....	24
Expert Systems Overview .....	27
3. FURTHER SENSITIVITY ANALYSES .....	39
Correlation Analysis of Driver's Maneuvering Behavior	
Parameters .....	40
Correlation Analysis of Impact Parameters .....	48
Summary of Sensitivity Analyses .....	55
4. METHODOLOGY OF ACCIDENT SIMULATION	
CONVERGENCE .....	58

Objective Function .....	58
Contributing Variables Selection .....	60
Blocked Coordinate Descending Algorithm .....	61
Convergence Engine Development .....	65
Automatic Coordinate Converging System Implementation .....	72
 5. EVALUATION OF ACCIDENT SIMULATION CONVERGENCE .....	 83
RICSAC Simulation Results without Optimization .....	83
RICSAC Simulation Results with Optimization .....	87
 6. CONCLUSIONS AND RECOMMENDATIONS .....	 99
Conclusions .....	100
Recommendations .....	106
 APPENDICES	
A CORRELATION COEFFICIENT VALUES OF DRIVER'S MANEUVERING PARAMETERS ANALYSIS .....	 108
B CORRELATION COEFFICIENT VALUES OF IMPACT PARAMETERS ANALYSIS .....	 112
C OPTIMIZED INPUT DATA SETS FOR RICSAC CASES .....	113
REFERENCES .....	123
BIOGRAPHICAL SKETCH .....	126

## LIST OF TABLES

<u>Table</u>	<u>page</u>
4.1 Step Widths in Different Levels at Each Converging Task .....	72
5.1 Impact/Rest Positions of 10 Usable RICSAC Staged Crash Tests .....	84
5.2 Final Rest Positions without Optimization .....	85
5.3 Path Errors without Optimization .....	86
5.4 Converging Sequences for Testing Combinations .....	88
5.5 Path Errors of Converging Sequence A .....	89
5.6 Path Errors of Converging Sequence B .....	90
5.7 Path Errors of Converging Sequence C .....	90
5.8 Path Errors of Converging Sequence D .....	91
5.9 Optimized Objective Function Values for Various Converging Methods .....	92
5.10 Final Rests after Optimization .....	93
5.11 Path Errors after Optimization .....	94
5.12 BCD Optimized Impact Speed Errors .....	96
5.13 BCD Optimized Impact Configuration .....	97
5.14 BCD Optimized Impact Configuration Errors .....	98

## LIST OF FIGURES

<u>Figure</u>	<u>page</u>
1.1 The Feedback Loop for Conventional Accident Simulations .....	3
1.2 The Feedback Loop for Automatic Accident Simulations .....	6
2.1 An Approach to Reconstruct a Two-Car Collision .....	15
2.2 Calculate Speeds for Different Mark Types .....	17
2.3 A Problem Space .....	29
2.4 Depth-first Search .....	30
2.5 Breadth-first Search .....	31
2.6 Node Order in Iterative Deepening .....	32
2.7 Node Order in Iterative Broadening .....	32
3.1 Correlation Analysis of Driver's Inputs vs coordinate Changes .....	41
3.2 The Influence of SPEED and STEER on X, Y and H when All Wheel Forces Are Zeros .....	43
3.3 Influences of SEED and STEER on X Changes .....	44
3.4 Influences of SPEED and STEER on Y Changes .....	45
3.5 Influences of SPEED and STEER on H Changes .....	46
3.6 The Influence of Driver's Inputs on Coordinate Changes When STEER Is Zero .....	47
3.7 Impact Configuration of RICSAC Test #8 .....	51

3.8	Oblique Collision Correlation Analysis of Speed, Crush Stiffness and Inter-Vehicle Friction .....	52
3.9	Impact Configuration of RICSAC Test #11 .....	53
3.10	Collinear Collision Correlation Analysis of Impact Speed, Crush Stiffness and Inter-Vehicle Friction .....	54
4.1	Trajectory Convergence Stages Context Diagram .....	61
4.2	Original Control Flow of EDSMAC .....	65
4.3	A Modified Control Flow for EDSMAC .....	66
4.4	A Simulation Control Flow .....	67
4.5	Context Diagram for Convergence Engines .....	68
4.6	The General Flow Chart of convergence Engines .....	69
4.7	ACCS Input Session Screen 1 .....	73
4.8	ACCS Input Session Screen 2 .....	73
4.9	ACCS Input Session Screen 3 .....	74
4.10	ACCS Input Session Screen 4 .....	75
4.11	ACCS Input Session Screen 5 .....	75
4.12	ACCS Input Session Screen 6 .....	76
4.13	EDSMAC Input Session Screen 1 .....	77
4.14	EDSMAC Input Session Screen 2 .....	77
4.15	EDSMAC Graphical Output -- Pre-Impact Phase .....	78
4.16	EDSMAC Graphical Output -- Impact Phase .....	79
4.17	EDSMAC Graphical Output -- Post-Impact Phase .....	80
4.18	EDSMAC Graphical Output -- Final Rest Positions .....	81

4.19 A Screen of the Simulation Processing Session of EDSMAC (Text Mode) .....	82
4.20 A Screen of the Output Session of EDSMAC .....	82

Abstract of Dissertation Presented to the Graduate School  
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IMPROVED CONVERGENCE IN  
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Major Department: Civil Engineering

Traffic accident simulation is a very powerful method of supporting the conclusions of an accident reconstruction. However, two technical problems exist in the process of conducting a traffic accident simulation. The first problem is the excessive amount of time required to conduct the simulation. The second problem is that more than one set of input parameter combinations can produce a satisfactory result. Thus, to improve the quality of accident simulation, it is necessary to have a systematic and efficient approach to conduct the trial and error process to reproduce a simulated scenario that more accurately reflects the physical evidence.

A blocked coordinate descending (BCD) converging algorithm is proposed in this dissertation as a means of improving the convergence of traffic accident simulation results.

This algorithm was modified from a hill-climbing algorithm, and divides a large converging task into several smaller converging tasks. BCD improved the converging efficiency while maintaining adequate accuracy.

The most significant contributing factors (i.e. speed, steering angle, braking or accelerating wheel forces, etc.) that affect the simulation results of cases where a single vehicle loses control and the factors (i.e. impact speed, impact configuration, wheel forces, post-impact steering angle, etc.) that affect the simulation of cases where two cars collide were analyzed. An automatic coordinate converging system (ACCS) was developed to conduct the convergence.

The impact configurations and final rest positions of ten staged collision cases was used to evaluate the performance of the ACCS system. The results show that the performance of converging simulation results with staged collisions are effectively and efficiently improved by using a BCD converging algorithm.

## CHAPTER 1 INTRODUCTION

### Statement of the Problem

Automobile accidents happen every day on the highway system. They cost the U.S., one of the most advanced countries in automobile manufacturing and highway system building, over 40,000 fatalities annually. Not only do the victims of traffic accidents suffer but families and friends of these victims are hurt through the loss or injury of their loved ones. From a broader perspective, the whole nation is a victim of traffic accidents due to the loss of life of many of our most promising citizens (from 1975 to 1991, the age group of 16 to 64 represented 67.51% of the total highway fatalities [1]) and as a result of the cost of hospitalization and social welfare for the injured.

The development of techniques to determine how an accident occurred is one of the efforts designed to alleviate loss in traffic accidents. Though reconstructing an accident does not prevent it from happening, discovering actual contributing factors to accidents does help in designing and building safer cars and highway systems as well as in making better traffic laws. In litigation, the result of a reconstruction can help the judge and jury decide how much tort liability each entity involved in the accident should have.

Traffic accident reconstruction and traffic accident simulation are two ways of discovering how an accident happened and how it might have been avoided. Accident reconstruction determines the manner of occurrence of an accident by using the physical

evidence at the scene, testing any evidence and the laws of physics and engineering. Accident simulation reproduces an accident scenario by running a simulator with results from a reconstructed conclusion or from data derived from a hypothetical pre-collision situation.

In the process of reconstructing an accident, the final rest positions of both vehicles must first be located. Second, one must identify the location where the impact occurred. Third, the trajectories of both vehicles before and after the impact must be determined. Fourth, the approaching angles and departure angles of both vehicles in the collision must be determined. Finally, by applying the laws of linear momentum and other basic physics, the impact and initial speeds of both vehicles can be calculated to arrive at an explanation of the collision.

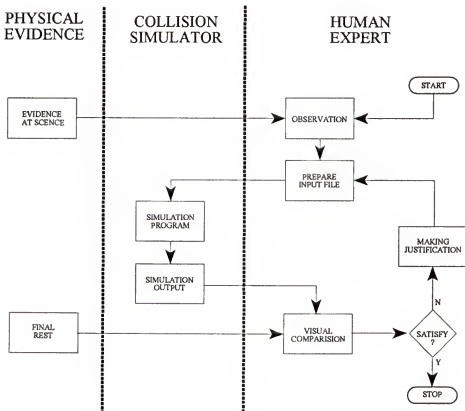
Accident simulation is another approach used to determine how an accident occurred. A simulator is a computer program that produces a post-impact scenario every time an assumed set of initial conditions is input. These conditions include all of the pre-impact information about the accident, such as the initial locations, speeds and approaching angles of both vehicles, etc. A simulator then generates a scenario based on this information. If the simulated scenario follows the same trajectories and falls on the same final rest positions indicated by the evidence, then this scenario is probably a reasonable explanation of how the accident happened.

If information could be obtained in a controlled fashion, as in a staged collision, accident reconstruction would not be a difficult task. However, in most cases there is some information missing. Simulation is a very powerful approach to finding the missing information. A simulator is a useful tool to conduct the what-if analysis for this purpose. By

giving the simulator a best assumption about the missing information, the simulator then produces a scenario based on the assumed information. If the scenario happens to be consistent with the physical evidence, the missing information has probably been found.

Though traffic accident simulation is a very powerful method that supports the conclusion of an accident reconstruction, there are some technical problems which exist in the process of conducting a traffic accident simulation:

1. It is very time consuming. Traffic accident simulation is a trial and error process. A reconstructionist (human expert) gives an assumed set of initial conditions, based on his/her observation on the evidence at the scene, to a



**Figure 1.1** The Feedback Loop for Conventional Accident Simulations

simulator to see whether or not the simulation result satisfies his/her expectations. If the result is not good enough, the user then needs to go back to modify the initial conditions and run the simulation again (shown as Figure 1.1). Each simulation takes several minutes during which time the analyst is tied up watching the screen and, if the simulated results deviate too much from the physical evidence, the analyst must change the appropriate input parameters for the next simulation in a manual feedback process. This process continues until a satisfactory simulation result is obtained. The length of time that is needed to come up with a "satisfactory result" usually depends on how much effort a reconstructionist is willing to devote.

2. There may be more than one satisfactory input combination. An even more frustrating fact is that there may be an infinite number of combinations. Every parameter in the initial conditions may have some impact on the simulation result. Since there are an infinite number of points between two real numbers, there may be an infinite number of combinations of initial conditions if the trial and error process is conducted in a random manner. Not only that, even if a "satisfactory result" is achieved, there is not much confidence that a reconstructionist can say that this is the best simulation result.

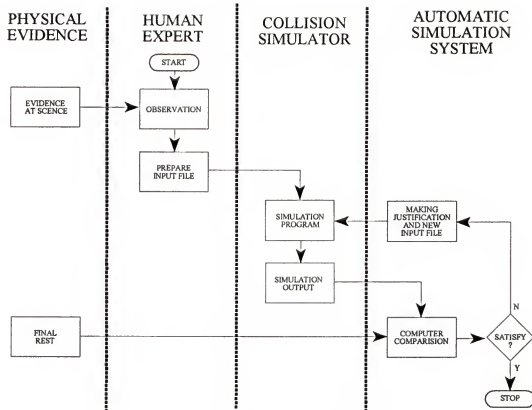
Thus, to improve the quality of accident reconstruction, there is a need for a systematic and efficient approach to conduct the trial and error process to reproduce a simulated scenario that will fit most of the valid physical evidence and witnesses' statements.

## Objectives, Study Scope and Limits

### Objectives

Ideally, the final goal of an accident simulation is to produce a simulation scenario in which the simulated post-impact vehicle trajectories are substantially similar to the actual vehicle trajectories and in which the final rest positions of the vehicles in the simulation match the actual final rest positions of the vehicles in the crash. One major reason for the delay in developing an efficient systematic approach to reproduce a "good" scenario is that most of the knowledge possessed by experts on how to converge simulation trajectories on the physical evidence is heuristic and case dependent. Without a solid algorithm for solving certain types of problems a conventional program for that purpose can never be developed. This is a constraint to any conventional software. Thus, even though great simulation programs like HVOSM [2], SMAC [3], TBST [4], TBSTT [5], etc. are available, if a reconstructionist wants to know how a slight adjustment of input will affect the simulation output, he/she still has to run these programs manually.

However, if all contributing factors of an accident simulation program can be found, by systematically choosing one or a group of these factors at a time and using expert systems searching and converging techniques to justify the value of these factors, the constraint mentioned above could be overcome and the chances of converging simulation results on the physical evidence collected at the scene could be significantly improved.



**Figure 1.2** The Feedback Loop for Automatic Accident Simulations

Thus, there are three objectives to be accomplished in this study:

1. Finding the most significant contributing factors that affect an accident simulation program.
2. Developing a generalized systematic approach that improves the convergence of trajectories in traffic accident simulation.
3. Establishing a generalized traffic accident automatic simulation system by using expert systems searching and converging techniques to eliminate the manual feedback loop and self-iterates until a satisfactory convergence is achieved (shown as Figure 1.2).

### Scope

EDSMAC (Engineering Dynamic Simulation Model of Automobile Collision) [6] is a generally accepted two-car collision simulator in the accident reconstruction field and will be used as the simulation tool to simulate two-car collision cases. In two-car collision cases, the study will focus on how to best reproduce the post-impact trajectories of both vehicles given information about the impact configuration such as crush stiffness, wheel forces, impact speed, position of collision, as well as the post-impact steering angle of each vehicle.

### Limits

Due to the constraints of the simulation tool, the accident cases must be limited to the following:

- (1) The number of vehicles involved is limited to two.
- (2) Vehicles remain on the same ground plane, before, during and after the impact, without having any flip-over, vault or fall movements.
- (3) None of the vehicles involved are articulated vehicles.
- (4) The mass of any of the vehicles remains the same throughout the whole process of the collision.

## CHAPTER 2

### LITERATURE REVIEW

Articles regarding traffic accident reconstruction, traffic accident simulation, expert systems, and expert systems techniques in searching and convergence are reviewed and summarized. The author's reviews and assessment of the prospective convergence method in accident trajectory simulations are also presented.

#### Accident Reconstruction Overview

Traffic accident reconstruction attempts to explain exactly what happened in an accident before, during, and after an impact, and to determine precisely what factors contributed to the cause of the accident. Limpert [7] divided reconstruction into three distinct sections, namely:

1. The Facts Section:

This includes all objective data (usually considered facts) such as vehicles, drivers, the roadway involved in the accident, as well as scene photographs and measurements. Some facts may be questionable depending upon the specific circumstances of an accident and the data collection and documentation done. For example, scene photographs may or may not identify a certain tire mark as made by a locked or rotating tire, or a specific scene measurement made by the investigating officer may be suspect. The

accident reconstructionist must compile as many facts as possible. Likewise, the investigating officer generally tries to identify, interpret and document facts during the investigation of the accident and, in particular, the critical points essential for a valid reconstruction of an accident.

2. The Engineering Analysis Section:

This includes all engineering equations, analyses, testing, and mathematical models which clearly, reasonably, and accurately describe the motions and associated physical parameters of the vehicle(s) and occupants involved in the accident. For example, a single vehicle truck rollover requires different engineering equations than a car/pedestrian accident. When computer programs are used, care must be taken to understand the principles and mathematical computations behind these problems rather than accepting them as black boxes.

3. The Witness Statement Section:

This includes all statements made by witnesses to the accident. The main reason for initially separating accident data provided by witnesses from accident facts is that one cannot go to witnesses and objectively verify the truth of their statements. Witnesses are not trained in observing transient events such as a rolling vehicle and normally do not practice watching accidents. Furthermore, witnesses experiencing an immediate accident threat, such as a driver or passenger, may panic and may not be able to clearly observe and recall specific events later. Uninvolved witnesses usually provide

more accurate accident data. However, all witness data must "pass" through the engineering analysis section to ensure reasonable accuracy. Witness data shown to be fundamentally inconsistent with objective data and the basic accident physics developed in the engineering analysis section must be discarded.

The results of the reconstruction are statements that indicate how the collision occurred, why it happened, and whether it could have been avoided.

#### Data Needed in Accident Reconstruction

The accuracy of a traffic accident reconstruction is primarily dependent upon the quantity and quality of information available. McHenry [8] listed the accident evidence required for the application of any reconstruction or simulation program:

1. Make, model and year of vehicles manufacture.
2. Measured weights and/or definition of passenger and cargo loading of each vehicle.
3. Directions of principal forces (estimated from damage).
4. Damage dimensions.
5. Rest positions and orientations.
6. Impact positions and orientations.
7. Braking resistances of individual wheels of each vehicle (i.e., brake application, engine braking, tire/wheel damage, etc., may be a function of time).

8. Tire marks and tracks.
9. Measured friction coefficient(s) and/or description(s) of surface type(s) and condition(s).
10. Definitions of boundaries between terrain zones with different friction properties.
11. Direction and extent of yaw rotations.
12. Evidence of control inputs before and after impact (i.e., steering, braking, acceleration may also be a function of time).
13. Intermediate positions on curved spin out trajectories.

Some of these data are relatively easy to obtain by simple inspection or measurement (e.g., 1, 2, 4, 5, 8, 9 and 10 in the list above) and are relatively credible. Other data, which are deduced from some minor evidence or experience obtained from a reconstructionist (such as 3, 6, 7, 11, 12 and 13 in the list above), are more questionable and make the reconstruction much more complex.

### Systematic Procedure

#### General Procedure

Baker and Fricke [9] have developed certain useful approaches that are applicable in many typical accident reconstruction cases. Some of the steps described below apply to every accident reconstruction problem; others are less generally applicable.

1. State the problem or problems. Clearly identify the issues to be resolved. This immediately sets limits on the work you have to do.

2. Review the data available. Put aside any data which appear to be irrelevant -- for example, descriptions of injuries when the issue is which vehicle was on the wrong side of the road. Reviewing the data reveals what information you have to go on and enables you to sort out information which may be useful from that which clearly is not.
3. Consider the need to obtain more data. From the examination of data at hand, it may appear at once that additional useful material might be available -- for example, certain photographs, statements of informants, or measurements. Or, it might seem desirable -- or even necessary -- to try to secure additional data, such as weights of vehicles, further details from witnesses, or locations of traffic control devices.
4. Prepare a working after-accident situation map.
5. Work back. Calculation of speed from a braking skid mark or a turning yaw mark is a form of working back. In such cases, the mark on the road is the result of the accident from which one begins to work back. First, one must clearly recognize just how this mark was made. Then the length of slide or radius of turn must be determined. Next, the resistance of the surface to sliding must be estimated. Finally, principles of mechanics are applied to discover what speed would have been required to slide to a stop in the given distance or to turn the indicated radius.
6. Testing theories (hypotheses) may adequately resolve issues if working back does not yield satisfactory solutions to problems.

7. Consider whether all reported results of the accident are satisfactorily accounted.
8. Test the conclusions reached.

#### Detailed Procedure

1. Draw an outline of each vehicle approximately to scale and preferably to the same scale as the after-accident situation map.
2. For each vehicle study the damage (or photos of the damage) and show its collapsed or deformed shape on the vehicle outline.
3. Also indicate on the outline, by a bracket with a pointer at each end, the extent of the contact damage area.
4. Locate the spot of greatest collapse, penetration, or distortion in the contact damage area, and then estimate the direction a vehicle part was moved to force it to that position. Show this on the outline as a thrust arrow.
5. Consider carefully how the direction of thrust (force line) is related to the center of mass of the vehicle.
6. Put the vehicles together at maximum engagement position. Put a tracing of one vehicle outline over the outline of the other or use cutout patterns of the two vehicles. Adjust these so that the maximum engagement deformation of each is against that of the other and the thrust arrows are aligned.
7. Compare carefully the direction of rotation and its rate for the vehicles involved. This is the basis for estimating the change in angle between the

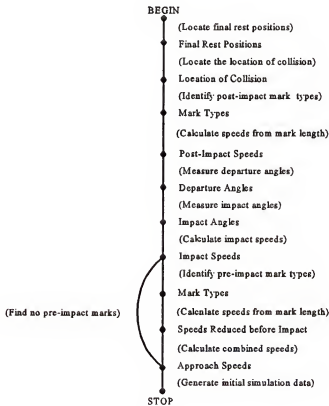
vehicles from first contact to maximum engagement. Then adjust the positions of original outlines (which do not show damage) to represent first contact positions.

8. Do the same to show the positions of the vehicles at separation.
9. Go to the after-accident situation map. Look for signs of the first contact position: mainly irregularities in tire marks but sometimes scars on fixed objects. Look for signs of the maximum engagement positions: collision scrubs, gouges, scrapes, spatter. Place the outline of the two vehicles on the map. Put maximum engagement outlines on the signs of maximum engagement, and so on. If there are no signs on the map of first contact or maximum engagement, place the outline according to the statement of a witness, if any, or according to some theory of what happened.
10. Think about how each vehicle would move from its maximum engagement position to its final position. Consider how it must rotate and translate (move).
11. Try to account for all signs of the accident: tire marks, gouges, debris and so on -- reported or showing in photographs. If any seems not to be associated with the accident, be prepared to explain exactly what makes you think so.

### A Systematic Procedure

To sum-up the findings of this section, a systematic approach to reconstruct a typical two-car collision is illustrated as Figure 2.1, consisting of the following ten steps:

- Step 1:        Locate the final rest position of each vehicle and record the coordinates. This includes the coordinates of each vehicle's center of mass, tires, and heading angle.
- Step 2:        Find the location of the collision. The location of the collision is very crucial to accident reconstruction. Usually the location of gouges, scrapes, fluid, debris, the end of pre-impact skid marks, or the



**Figure 2.1**    An Approach to Reconstruct a Two-car Collision

diversion of marks indicates where the collision occurred. However, sometimes none of the above were recorded by the investigator. A reconstructionist, then, needs to run a simulation based on witness' statements to derive a possible collision location.

- Step 3: Identify the type of marks between the final rest and colliding location. There are three different types of marks that a vehicle can leave on the pavement when it comes to a quick stop due to the friction of the pavement. Yaw marks indicate that the vehicle was side sliding to a stop without braking. Scuff marks indicate that the vehicle was rotating to a stop with either no or partial braking. Skid marks indicate that the vehicle was sliding to a stop with its wheels fully locked up.
- Step 4: Calculate speeds for different mark types. Figure 2.2 illustrates this step in detail. When a vehicle leaves skid marks or scuff marks, the distance between the final rest and the colliding location must be measured. The speed of a vehicle sliding distance may be calculated by using the equation

$$S = \sqrt{30 \times D \times f} \quad (2.1)$$

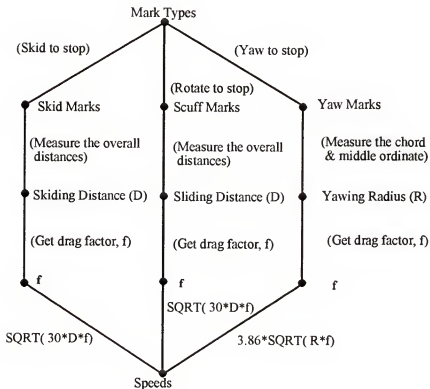
where

$S$  = Speed in miles per hour

$D$  = Sliding distance in feet

$f$  = Drag factor (deceleration rate in g's).

The only difference between speeds calculated for skuff marks and speeds calculated for skid marks is that for skid marks the drag factor is equal to the coefficient of friction; for skuff marks the drag factor is less than the coefficient of friction. When yaw marks are left, the necessary measurements to calculate speed are the chord of the curve,  $C$ , and the middle ordinate of the chord,  $M$ . The radius,  $R$ , can then



**Figure 2.2** Calculating Speeds for Different Mark Types

be calculated by using the equation

$$R = \frac{C^2}{8M} + \frac{M}{2} \quad (2.2)$$

and the speed can be calculated by using the equation

$$S = 3.86 \sqrt{R \times (f \pm m)} \quad (2.3)$$

where

$f$  = the coefficient of friction (full drag factor)

$m$  = the super elevation of the pavement.

- Step 5: Measure the departure angles for each vehicle.
- Step 6: Measure the impact angles for each vehicle.
- Step 7: Calculate the impact speed of each vehicle by using the conservation of linear momentum.
- Step 8: If pre-impact marks do not exist, go to step 10. If they do exist, mark types must be identified and speeds must be calculated, as in step 3 and 4. However, speeds obtained here are the speeds reduced before the collision.
- Step 9: The impact speed and pre-impact speed of each vehicle must be combined with the equation

$$S_{\text{Combined}} = \sqrt{S_{\text{Pre-impact}}^2 + S_{\text{Impact}}^2} \quad (2.4)$$

where

$S_{\text{combined}}$  = Combined speed

$S_{\text{pre-impact}}$  = Pre-impact speed

$S_{\text{impact}}$  = Impact speed.

Step 10:       Generate the reconstruction report for this accident.

### Computer Programs for Accident Reconstruction

It can be a truly formidable task for the accident reconstructionist to simultaneously solve mathematical equations resulting from conservation of momentum and energy principles, coupled with the force-deformation characteristics of vehicles, often including human factors characteristics of drivers interacting with unusual roadway geometric design features. Using computer programs specifically designed to analyze and reconstruct traffic accidents saves the reconstructionist time and effort. There are many different programs available that offer versatility and easy manipulation.

#### Programs for Mainframe Computers

The computer programs described here were written for large, mainframe computers. The Highway Vehicle Object Simulation Model (HVOSM) program [2, 10] was the first program developed under Federal Highway Administration Contract CPR-11-3988, between 1966 and 1971 by Cornell Aeronautical Laboratory, now called Calspan. The first version of HVOSM modeled the collisions of vehicles with fixed roadside objects. The force generated by the collision was assumed to be a linear function of the vehicular deformation. The

program could also compute the trajectories of a vehicle under launch, vault, and other maneuvers, and has been used successfully to predict the trajectories of a vehicle subjected to unusual roadway geometrics.

The Simulation Model of Automobile Collision (SMAC) program [3, 11] was also developed under contract to the U.S. DOT by Calspan in the early 1970s. It modeled the collision between two vehicles in a two-dimensional, rectangular grid system. The impact force resulting from the collision is also modeled by a linear force-deflection function, similar to the impact force model of the HVOSM program. After the initial conditions of velocity and position of the mass center in two rectangular coordinates and one yaw coordinate representing the angular orientation are provided for each vehicle, the program uses numerical integration of the dynamic equations governing the impact of vehicles to tabulate the positions, velocities, and accelerations of both vehicles up to their final rest positions.

The third computer program developed by Calspan for the U.S. DOT in the 1970s, Calspan Reconstruction of Accident Speeds on the Highway (CRASH) is used more often than HVOSM and SMAC. An important feature of this program is a method developed by Campbell [12] that computes the change in vehicular velocity due to impact, called "delta-V," from the "crush depth" deformation data of the vehicular collision. Combining the work-kinetic energy principle with the conservation of linear momentum principle, this program computes pre-impact speeds and speed changes due to the collision, as well as other accident parameters desired by the reconstructionist. An important parameter required as input for this program is the "principal direction of force" acting on each vehicle during the collision. The accuracy of the computed variables depends on the accuracy with which this input parameter

is estimated. The actual crush depth/"delta-V" relationships for the vehicles involved also affect the accuracy of the computed pre-collision variables desired.

The TBST and TBSTT (Truck Braking and Steering) programs were developed at the University of Michigan Transportation Research Institute (UMTRI) by a group of researchers headed by H. Moncartz under sponsorship by the Motor Vehicle Manufacturers Association (MVMA) [4, 5]. TBST is a single-vehicle simulator (SVS) and TBSTT is a vehicle-trailer simulator (VTS). These computer simulation programs are useful for studying the response of a vehicle to braking and steering efforts by the driver. Accident reconstructionists use these simulation programs to determine how control loss of a vehicle (as a result of excessive speed, braking, over-correction, and other driver-related errors) occurs.

The PHASE4 program is the culmination of a major effort undertaken at the University of Michigan [13]. This program is a vehicle dynamics simulator (VDS) used to simulate the response of a single vehicle or vehicle-trailer combination (up to triples) to driver braking and steering. The program has very elaborate methods for studying tires, suspensions, and anti-lock braking systems. It also requires a substantial amount of input data. Because the simulated vehicle is not limited to a flat highway, the program is well suited to analyses beyond the scope of simpler programs. Such applications include the study of truck rollovers at highway off-ramps having a grade, super-elevation and spiral curve.

In Europe, the Equivalent Energy Speed-Accident Reconstruction (EES-ARM) program [14] has been developed by Daimler-Benz to model automotive collisions. Similar to the CRASH program, it requires an input parameter of an "energy equivalent speed" for

each vehicle, which closely approximates the crush depth/"delta-V" relationship of CRASH. It combines the principles of conservation of momentum and the work-kinetic energy relationships to compute dynamic vehicular parameters.

#### Programs for Microcomputers

Today, many microcomputer versions of traffic accident reconstruction programs, such as IMPAC [15], BLAQ BOX [16], ATAC I [17], TAAR-2 [18], EDVAP [6], etc., are available. All of these microcomputer programs utilize the dynamic principles of conservation of momentum and of work-kinetic energy along with vehicular crush depth/"delta-V" energy relationships to mathematically model the mechanics of traffic accidents to compute the desired kinematic variables as they existed just before, during, and immediately after a traffic accident. Among these programs, it is necessary to give the EDVAP package a further introduction because of its importance to this study.

#### EDVAP package

EDVAP (the Engineering Dynamics Vehicle Analysis Package) is one of the most powerful accident reconstruction tools available on PCs in today's software market. It is generally accepted as the standard in the accident reconstruction field. Information gained from accident site measurements and vehicle inspections is used, in conjunction with vehicle dynamics and the laws of motion, to analyze events surrounding an accident.

EDVAP is a series of five vehicle dynamics programs useful in the study and presentation of motor vehicle accidents:

- EDSVS (Engineering Dynamics Corporation Single Vehicle Simulator) is produced from Moncartz' TBST program and analyzes the response of a single vehicle to braking, acceleration, and steering in the horizontal plane.
- EDVTS (Engineering Dynamics Corporation Vehicle Trailer Simulator) is produced from Moncartz's TBSTT program and analyzes the response of a vehicle/trailer to braking, acceleration, and steering in the horizontal plane.
- EDCRASH (Engineering Dynamics Corporation Reconstruction of Accident Speeds on the Highway) is produced from the CRASH program and reconstructs the vehicle velocity at impact and velocity change as a result of collision in the horizontal plane.
- EDSMAC (Engineering Dynamics Corporation Simulation Model of Automobile Collisions) is produced from the SMAC program and simulates vehicle dynamics at impact and velocity change as a result of collision in the horizontal plane.
- EDCAD (Engineering Dynamics Computer-Aided Drafting) develops a scaled accident site drawing that can be combined with output from other EDVAP analysis programs.

The aforementioned programs are integrated. The output file of one program can be a portion of the input file to another program.

EDVAP can be used to test various possible accident scenarios and can determine how sensitive the analysis is to certain unknown parameters. After any of the programs have been executed, users can study the effects of changing any variable simply by changing that

variable and re-executing. Changes can be made to an isolated variable or set of variables to identify their effects on the outcome. Only the changed input variables need to be entered. The program saves all the previously entered information.

#### Sensitivity of Selected Variables in EDSMAC and Converging Procedure

Traffic accident simulators are very useful for analyzing accidents. To make the best use of a simulator, a user should understand how sensitive the simulator's input parameters are. For EDSMAC, Day and Hargens [19] studied the effect of changing selected parameters on the simulated vehicle paths and damage profiles. Their study produced the following findings:

1. Increasing the center of gravity offset tends to decrease path length, to increase heading change and to decrease crush depth.
2. Increasing the linear velocity tends to increase path length, heading change, and crush depth.
3. Increasing the angular velocity tends to decrease path length, increase heading change, and does not significantly affect crush depth.
4. Increasing the vehicle weight tends to decrease heading change, increase crush depth, and may increase or decrease path length.
5. Increasing the yaw moment of inertia tends to decrease heading change but does not significantly affect path length and crush depth.
6. Increasing the crush stiffness tends to increase heading change, decrease crush depth, and may increase or decrease path length.

7. Increasing the inter-vehicle friction tends to decrease path length, heading change, and does not significantly affect crush depth.
8. Increasing the restitution tends to decrease crush depth and may increase or decrease path length and heading change.
9. Increasing the tire-ground friction tends to decrease path length and heading change but does not significantly affect crush depth.
10. Increasing wheel forces as balanced braking or accelerating tends to decrease and increase path length respectively, but does not significantly affect crush depth and heading change.
11. Increasing the steering tends to increase heading change and does not significantly affect path length or crush depth.

In the same study, Day and Hargens also proposed a procedure which helped to quicken the process of achieving a satisfactory match between predicted and actual results.

This procedure began with the following steps:

1. In selecting prospective testing parameters, the following steps can be helpful in developing a list containing only those parameters which are capable of effecting the desired changes.
  - (1) Identify the difference(s) between the predicted and measured results. Usually, the results of interest are (a) rest position and heading and (b) damage profiles.

- (2) Identify the unknown or estimated input parameters and their associated possible ranges. Eliminate the remaining parameters from consideration.
  - (3) Identify those unknown or estimated parameters which have the greatest effect on the identified differences. Eliminate the remaining parameters from consideration.
2. The process for improving the match between the predicted and actual paths and damage profiles is outlined below:
  - (1) Select one of the parameters. Modify its value and identify its effect on the results. By reducing or increasing its value, determine if the match was improved or made worse.
  - (2) If the match was not suitably improved, select a second parameter and repeat the process.
  - (3) If necessary, repeat the process for all the significant parameters until a satisfactory match is achieved.

Note that input parameters affecting the impact phase were always tested first. This was necessary because changes to these parameters affected the separation conditions. For example, if post-impact steering and braking were modified first, any subsequent changes to the crush stiffness, inter-vehicle friction or restitution would alter the separation conditions, thus requiring further changes to post-impact steering and braking.

It was also absolutely essential to vary only one parameter at a time. Otherwise, the necessary cause-effect relationship could not be established. When finished, several

parameters may have been changed during the matching process. The key point is that only one parameter was changed at a time.

### Expert Systems Overview

#### History of Expert Systems

Expert system technology is an outgrowth of research in artificial intelligence (AI) that began in the 1950s [20]. In the 1950s and 1960s early work in AI focused on psychological modeling and search techniques. Some of that work is utilized in expert systems, but the current focus is on representing and using knowledge of specific task areas. Production systems were developed in the 1970s based upon the early work in psychological modeling. In the 1980s, fundamental work on knowledge representation moved towards the use of object-oriented substrates.

The first noteworthy expert system was DENDRAL [21]. It was developed at Stanford University in the late 1960s. DENDRAL was designed to infer the structure of organic molecules from their chemical formulas and information, obtained by mass spectroscopy, about the chemical bonds present in the molecules. DENDRAL applied heuristic knowledge to a large search space.

DENDRAL was followed by MACDYMA, an expert system developed at the Massachusetts Institute of Technology for performing complex mathematical analysis, and by HEARSAY, an expert system developed at the Carnegie Mellon University to serve as a natural language interpreter. The first blackboard system was HEARSAY-II [20]. Blackboard systems utilize independent knowledge sources, each with its own inference engine and

knowledge base, to produce changes to a global blackboard which contains the emerging solution to a problem.

MYCIN, an expert system to diagnose blood diseases, was developed at Stanford University in the 1970s [22]. MYCIN was one of the first expert systems to handle uncertainty. Another expert system developed at that time was PROSPECTOR, a program for determining the location and type of ore deposits based upon geological information at a site [23].

### Expert Systems Techniques in Convergence

Achieving a best convergence is the same as searching for an optimal solution for a problem. A conventional computer algorithm searches through a data structure. An expert system, however, searches a problem space [24]. A problem space is a representation of the problem and all potential solution paths. Unlike a data structure that is predefined and already in existence, a problem space is generally, although not always, procedurally defined when an expert system begins its search. That is, the entire problem space is not created and then searched but, rather, is created as it is being explored.

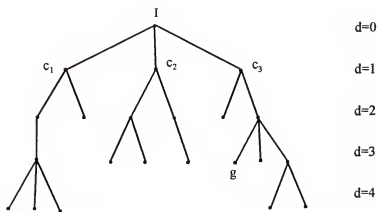
Because a random search cannot guarantee that this search will explore all paths in the problem space and thereby find a solution, some alternative methods that will be more systematic in the manner in which it explores the domain are needed.

Most of the systematic search methods fall into two major categories: exhaustive or blind search and heuristic or directed search [24, 25, 26].

### Exhaustive or blind search

Blind search is a type of systematic search which uses no knowledge of how close we are to a solution in picking the path to follow from our current location to a new location. There are a wide variety of blind search techniques including: depth-first, breadth-first, iterative deepening, and iterative broadening.

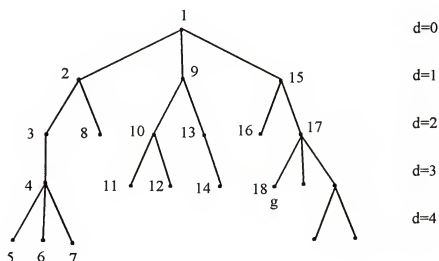
To illustrate these search techniques, let us assume that there is a search space like Figure 2.3. In the figure, the successors of the initial node  $I$  are the three nodes  $c_1$ ,  $c_2$  and  $c_3$ ; these are the nodes that can be reached from  $I$  in a single step. So the input to a search problem is a description of the initial and goal nodes and a procedure that produces the successors of an arbitrary node; the output should be a legal sequence of nodes starting with the given initial node  $I$  and ending with the goal node  $g$ .



**Figure 2.3** A Problem Space

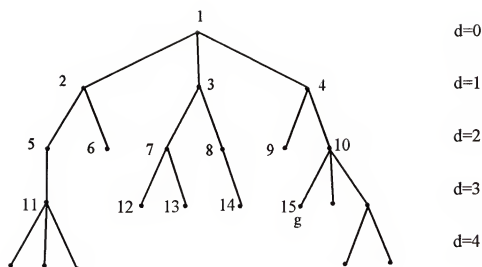
Depth-first search. A depth-first search can be thought of as expanding the search tree so that the terminal nodes are examined from left to right; the nodes are similar to the method explored in Figure 2.4. A child node of the most recently expanded node is always explored first. If this node has no children, the procedure backs up a minimum amount before choosing another node to examine. The search stops when the goal node  $g$  is selected.

Breadth-first search. In breadth-first search, the tree is examined from the top down,



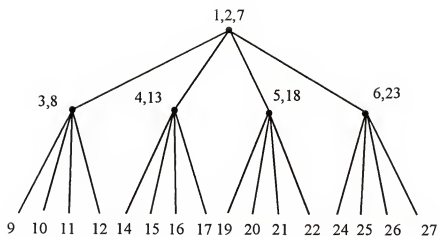
**Figure 2.4** Depth-First Search

so that every node at depth  $d$  is examined before any node at depth  $d + 1$ . Figure 2.5 shows the tree in Figure 2.3 being searched in a breadth-first order.

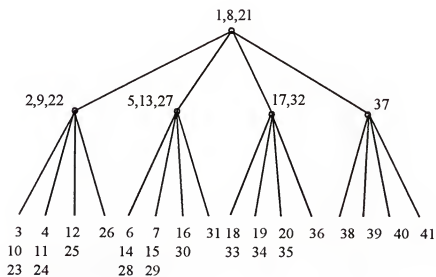


**Figure 2.5** Breadth-First Search

Iterative deepening. The idea of iterative deepening is to search the tree initially with an artificial depth cutoff of 1, so that any node below depth 1 is not examined. If this approach succeeds in finding a solution at depth 1, the solution is returned. If not, the tree is searched again but with a depth cutoff of 2. Each of these iterative searches proceeds in depth-first fashion. An example of the node ordering given by iterative deepening is shown in Figure 2.6.



**Figure 2.6** Node Order in Iterative deepening



**Figure 2.7** Node Order in Iterative Broadening

Iterative broadening. Just as iterative deepening imposes artificial depth limits on the search and gradually increases those limits until a solution is found, iterative broadening imposes artificial breadth limits, increasing them until a solution is found. An example of the node ordering given by iterative broadening is shown in Figure 2.7.

#### Heuristic or directed search

Instead of attempting to search every node in a tree, heuristic search takes a directed approach to search a tree. It moves steadily from the root node toward the goal by always selecting a node that is as close to the goal as possible.

There are an even wider variety of heuristic or directed search techniques: hill-climbing search, best-first search, and A\* search to name a few.

Hill-climbing search. If there is a simple function maximization problem such that we have a function  $f(p)$  that measures the interestingness of a point  $p$  on the surface, we need to find that value of  $p$  for which the function's value is maximal. In hill-climbing, always move in the direction of apparently largest  $f$ ; the functional analog is to attempt to find the global maximum of a function of many variables by always moving in the direction in which the rate of change is the greatest. The procedure could be listed as

1. Set  $L$  to be a list of the initial nodes in the problem, sorted by their expected distance to the goal. Nodes expected to be close to the goal should precede those that are farther from it.
2. Let  $n$  be the first node on  $L$ . If  $L$  is empty, fail.
3. If  $n$  is a goal node, stop and return it and the path from the initial node to  $n$ .

4. Otherwise, remove  $n$  from  $L$ . Sort  $n$ 's children by their expected distance to the goal, label each child with its path from the initial node, and add the children to the front of  $L$ . Return to step 2.

Best-first search. In best-first search one looks at the unexpanded nodes' estimates and continues the search from the node with the smallest estimates. This is very similar to the hill-climbing search, only in hill-climbing one always expands from the current position. The procedure of best-first search is:

1. Set  $L$  to be a list of the initial nodes in the problem.
2. Let  $n$  be the node on  $L$  that is expected to be closest to the goal. If  $L$  is empty, fail.
3. If  $n$  is a goal node, stop and return it and the path from the initial node to  $n$ .
4. Otherwise, remove  $n$  from  $L$  and add to  $L$  all of  $n$ 's children, labeling each with its path from the initial node. Return to step 2.

A\* search. The aim in best-first search is to find a goal as quickly as possible, which leads us to expand the node thought to be closest to a goal node. A\*'s aim is to find the shallowest goal as quickly as possible by expanding the node that appears to be closest to a shallow goal. Instead of ordering the nodes in terms of distance to the goal, one should order them in terms of the quality (that is, expected depth) of the nearest goal to them.

Suppose that we have a node  $n$  at depth  $d$  in the search tree, and that we judge this node to be a distance  $h'(n)$  from the nearest goal. This goal is therefore judged to be at depth  $d + h'(n)$  in the search space; it follows that instead of choosing for expansion the node with smallest  $h'(n)$  as in best-first search (since  $h'(n)$  is the expected distance to the goal), we

should choose for expansion the node with smallest  $d + h'(n)$ . The depth of the node being considered is also a function of the node, and is typically denoted  $g(n)$  and referred to as the "cost" of reaching the node  $n$  from the root node. Since our intention is to find a goal of minimal cost, we expand the nodes in order of increasing

$$f(n) = g(n) + h'(n). \quad (2.5)$$

This algorithm is known as the  $A^*$  algorithm and the procedure is:

1. Set  $L$  to be a list of the initial nodes in the problem.
2. Let  $n$  be the node on  $L$  for which  $f(n) = g(n) + h'(n)$  is minimal. If  $L$  is empty, fail.
3. If  $n$  is a goal node, stop and return it and the path from the initial node to  $n$ .
4. Otherwise, remove  $n$  from  $L$  and add to  $L$  all of  $n$ 's children, labeling each with its path from the initial node. Return to step 2.

### Expertise and heuristic knowledge

The general problem-solving methods and searching techniques described above were insufficient to solve the difficult research and application-oriented problems of the day. What was required was specific knowledge about the particular, limited application domains of interest rather than broad general knowledge that applied across many domains.

The knowledge represented in knowledge-based systems is that of experts in the domain. A part of an expert's knowledge consists of cause-and-effect relationships. These relationships or rules of thumb originate from the expert's past experiences and are commonly called heuristics. They represent informal knowledge, or shortcuts, that allow an expert to

quickly reach a solution to a problem without having to perform a detailed analysis of a particular situation, because either an analysis of a similar problem was successfully performed previously, or the relationship may have been learned as a result of a past failed attempt to solve a similar problem. The expert may not remember, or even know, all the details of the original problem analysis, but he/she recognizes that a particular approach worked once for a similar problem and that this same approach will probably work again for the problem at hand. An expert is able to utilize this basic knowledge to recognize quickly the salient features of the problem, categorize it according to these characteristics, and correctly devise a solution.

#### Convergence Techniques Selection

Searching methods in trajectories convergence that were introduced in the previous section include blind searches, directed searches, and expertise and heuristic knowledge. Blind searches do not meet our need for efficiency because they may take too much time and use up too much computer resource to reach a solution.

In directed searches, the A\* search is not applicable because the cost of a given node to the root node in the search space of trajectory convergence is unknown. Best-first search will take a longer time and need more computer resource than hill-climbing search because it not only expands from the best node in a search space but also retains in memory all the prior nodes. The hill-climbing search algorithm, hence, is the best prospective trajectory convergence technique because it can meet the goal of searching for the best result in a more efficient manner.

### Hill-Climbing and its Drawbacks

However, the strength of efficiency in hill-climbing is also a weakness of this algorithm. There are three drawbacks in hill-climbing worth noticing [27]. They are foothill, plateau and ridge problems.

**Foothill:** The foothills problem occurs when there are a number of small hills within the field that surround the tallest hill. When researchers encounter a foothill, they progress up its sides to its peak where they then stay since every direction they step from this point is lower. This peak is a local maximum rather than the global maximum within the field.

**Plateau:** The plateau problem occurs when the field is generally very flat and contains only a few very sharp peaks. As researchers explore the field, every point appears to be the same height unless they are lucky enough to encounter one of these peaks. The plateau provides no information to guide them toward the global maximum (or even local maximum).

**Ridge:** In the ridge problem, researchers find a path that leads them up the slope of the ridge, but once they are on the edge of the ridge they cannot find the proper direction to continue on toward the peak. The difficulty is that the ridge is very sharp (its sides slope off very quickly on both sides) and the number of directions that they are considering is not large enough to find a point higher on the ridge.

These drawbacks suggest that for rough search terrains, hill-climbing may only reach a local but not a global best solution.

### CHAPTER 3 FURTHER SENSITIVITY ANALYSES

Day and Hargens [19] conducted a sensitivity study on vehicle collision parameters and roughly summarized the effect of changing selected impact parameters on the simulated vehicle paths and damage profiles. However, they only stated the causation between input parameters and the results. The amplitude of each parameter's effect is still unknown.

To validate Day and Hargens' study and prioritize each significant parameter, two further sensitivity analyses were conducted in this study to analyze the strength of the influence of each contributing parameter on the simulation result. They are the correlation analysis of driver's maneuvering behavior parameters and the correlation analysis of impact parameters. The EDSVS program, a single vehicle simulator, served as a tool in the first analysis to simulate the interaction of driver's maneuvering parameters and vehicle path changes in which a single vehicle loses control. The EDSMAC program, a two-car collision simulator, served as a tool in the second analysis to simulate the interaction of impact parameters and the post-impact path changes of vehicles in two-car collision cases. Pearson correlation analysis was conducted in both analyses to find the strength of the influence of each of the parameters on vehicle's path changes.

### Correlation Analysis of Driver's Maneuvering Behavior Parameters

As part of this study total of 63,504 usable EDSVS simulations were executed with different driver's maneuvering behavior combinations and their results were collected. Variables used to represent the driver's maneuvering behavior are SPEED, STEER, and four wheel forces F1, F2, F3, and F4 where

SPEED : The initial speed of the testing vehicle,

STEER : The steer angle of front tires of the testing vehicle,

F1 : The wheel force of the right front tire of the testing vehicle,

F2 : The wheel force of the left front tire of the testing vehicle,

F3 : The wheel force of the right rear tire of the testing vehicle, and

F4 : The wheel force of the left rear tire of the testing vehicle.

Variables used to represent coordinate changes were

X : The change of the longitudinal distance,

Y : The change of the lateral distance, and

H : The change of the heading angle.

Testing ranges for the driver's maneuvering behavior were

SPEED : 10 -- 70 mph,

STEER : 0 -- 12 degrees,

F1 : 0 (free rolling) -- -1 (full brake),

F2 : 0 (free rolling) -- -1 (full brake),

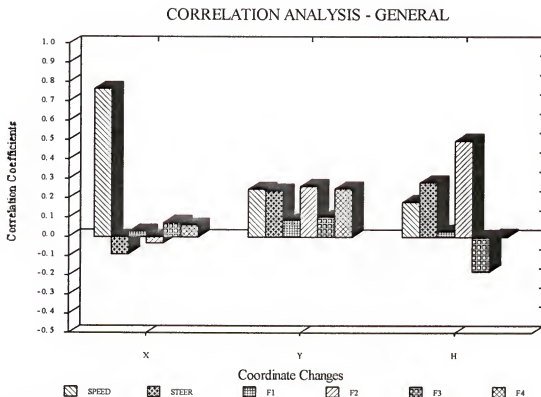
F3 : 0 (free rolling) -- -1 (full brake), and

F4 : 0 (free rolling) -- -1 (full brake).

To interpret the result of a correlation analysis, a positive correlation coefficient indicates that the coordinate change increases along with the influencing variable. A negative value then represents that the coordinate change increases when the value of the influencing variable decreases. The amplitude of the coefficient ranges from 0 to 1 represents from no relation at all to completely related. The detailed correlation coefficients of this analysis are presented as Appendix A.

### General Correlation Analysis

As shown in Figure 3.1, SPEED had the greatest effect on X changes, yet F2



**Figure 3.1** Correlation Analysis of Driver's Inputs vs Coordinate Changes

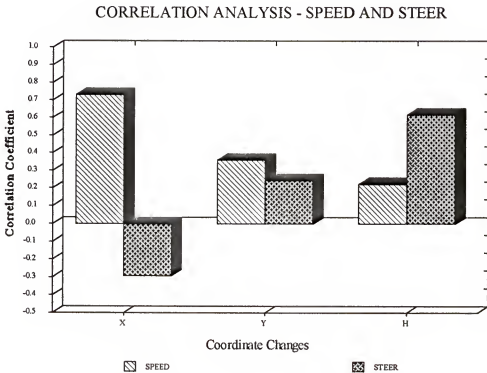
influenced H changes the most. For Y changes, variables of SPEED, STEER, F2, and F4 had almost the same of influence. The positive values that SPEED had on all X, Y, and H indicated that, with the interaction of STEER and wheel forces, X, Y, and H would increase if SPEED increased. STEER had positive values on Y and H but a negative value on X. This suggested that, with the interaction of SPEED and wheel forces, X would decrease, yet Y and H would increase if STEER increased.

However, the outcomes of this analysis had an inconsistency from the common sense point of view of the influence of each individual wheel force on X, Y, and H changes. In general cases, the left pair of wheels should have the same effect on coordinate changes as the right pair of wheels. The result of Figure 3.1 showed that the left front wheel, F2, had the largest influence on H of all four wheel forces. The sign of the influence of F2 was also opposite to that of the other three wheel forces on X. Among the other wheel forces, the magnitude of the influence of the right rear wheel, F3, on H was greater than the rest of the wheel forces and had an opposite sign from other wheels.

This discrepancy was caused by the interaction of STEER. Since STEER was tested only from 0 to 12 degrees, the testing vehicle had a right turning movement. This might cause each of the four wheels to have a different effect in terms of their influence on X, Y, and H. Thus, it is required to regroup the simulation data to conduct two more analyses to eliminate the cross influences between STEER and wheel forces on X, Y, and H changes.

### Correlation Analysis of SPEED and STEER

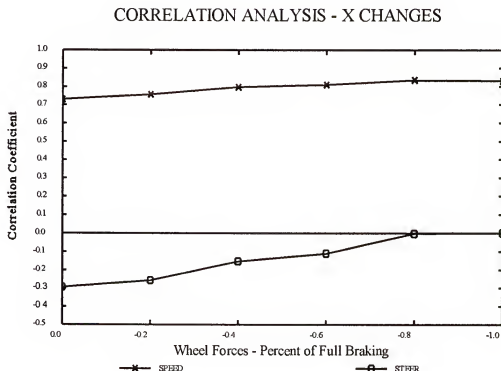
In this experiment all wheel forces were initiated as free rolling (0 braking force) to observe the influences of SPEED and STEER on X, Y, and H changes without the cross influence of any wheel forces. Figure 3.2 shows the result of this analysis. The signs of their influences on X, Y, and H were identical to the signs they had in Figure 3.1. The amplitude of their influences suggested that SPEED was more dominant than STEER on both X and Y changes, yet the changes of H were more dependant upon STEER than SPEED.



**Figure 3.2** The Influence of SPEED and STEER on X, Y and H When All Wheel Forces Are Zeros

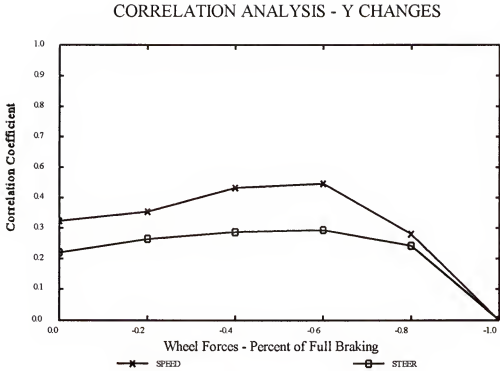
The influences of SPEED and STEER on coordinate changes vary when wheel forces are increased. The results of their changes on X, Y, and H are shown as Figures 3.3 through

3.5. In this experiment, all wheel forces were set to be equal in each test so that they would not offer any unbalanced influences on Y and H changes. The testing range of wheel forces in this experiment was from 0 (free rolling) to -1 (full brake) with an increment of -0.2.



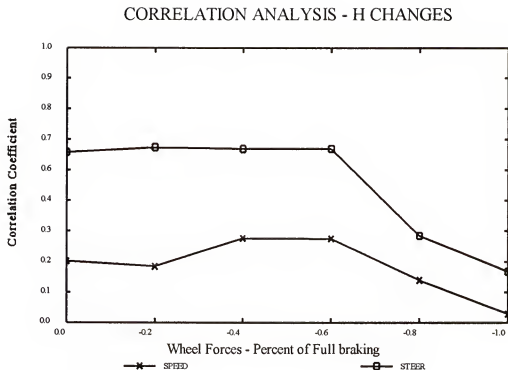
**Figure 3.3** Influences of SPEED and STEER on X Changes

Figure 3.3 shows how SPEED and STEER affect X changes at different braking levels. Figure 3.3 also indicates that SPEED had a significant positive influence on X at all braking levels and STEER, on the contrary, always had a negative influence on X at most of the braking levels. The influence of STEER on X also tends to be reduced when wheel forces increase. When wheel forces increased to a 0.8 braking level, STEER seemed to have no effect on X changes.



**Figure 3.4** Influences of SPEED and STEER on Y Changes

The influences on Y changes of SPEED and STEER are shown as Figure 3.4. SPEED also had a greater influence on Y than STEER at all braking levels. The magnitude of the influence of SPEED on Y was less than that on X. Unlike its influence on X, the sign of the influence of STEER on Y was opposite, which suggested that Y would increase when STEER increased. Both the influences of SPEED and STEER dropped to zero when full braking was applied. This fact is consistent with the laws of physics that when all wheels were locked up, neither SPEED nor STEER could change the lateral traveling distance of a sliding vehicle.

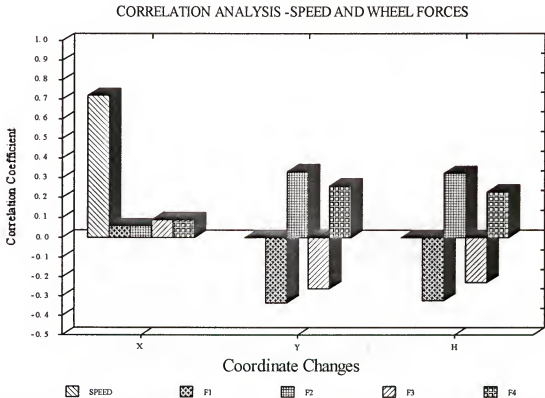


**Figure 3.5** Influences of SPEED and STEER on H Changes

Figure 3.5 shows that, with respect to H changes, the influence of STEER was more dominant than SPEED at all wheel force levels. When the braking was below a 0.6 level, the influence of STEER on H remained almost constant. After the 0.6 level, the influences of both STEER and SPEED started to drop. An interesting observation is that neither of these influences dropped to zero at the full braking level. This might indicate a possible round off error of EDSVS in calculating heading angle changes.

### Correlation Analysis of SPEED and Wheel Forces

In this analysis STEER was initiated as zero degrees to study the influences of each wheel force on X, Y, and H changes. Figure 3.6 shows the result of this experiment. In this test, SPEED was still the most dominant variable on X but had no influence on Y and H. Both right (F1, F3) and left (F2, F4) pairs of wheels had the same amount of influence on X, Y, and H but with opposite signs, with their counter part (left vs. right) except on X changes. On X changes, all wheels had positive coefficients which implies that if wheel forces increased X changes would decrease because the values of wheel forces were either negative or zero. Figure 3.6 also shows that the front wheels (F1 and F2) had a relatively greater influence on



**Figure 3.6** The Influence of Driver's Inputs on Coordinate Changes When STEER Is Zero

Y and H changes than the rear wheels (F3 and F4) and had a smaller influence on X changes than the rear wheels.

### Correlation Analysis of Impact Parameters

The impact parameters of two types of collisions were analyzed in this part of the study. They were oblique and collinear collisions. The impact configurations of two RICSAC staged collision tests were used in the EDSMAC program to conduct simulations for this purposes.

#### RICSAC Staged Collisions

The RICSAC (Research Input for Computer Simulation of Automobile Collisions) study was an analysis and reconstruction of 12 two-car staged collisions [28, 29, 30, 31]. The collisions were conducted at Calspan's Vehicle Experimental Research Facility (VERF) between November, 1977 and July, 1978. The surface at the facility had a tested friction coefficient of 0.87 [32].

Several impact configurations were tested. These configurations represented those typical of most real-world accidents, and included head-on (tests 11 and 12), rear-end (tests 3, 4 and 5) and intersection-type (tests 1, 2, 6, 7, 8, 9 and 10) collisions. Head-on and rear-end collisions were termed collinear, because the directions of their pre-impact velocity vectors are within 10 degrees of parallel; the remaining range was termed oblique.

After the collision, the site evidence was documented by Calspan's professional accident investigation team. This evidence included:

- wheel positions at impact and rest,
- locations of debris, skids, gouges, and spilled fluids, and
- vehicle trajectory.

### Impact Analysis Experiment Design

Impact configurations of RICSAC staged collision tests #8 and #11 were used as oblique and collinear examples respectively, in this study to analyze the effect of impact parameters on the simulated vehicles path changes.

Variables selected in this analysis were S1, S2, STIFF1, STIFF2 and FRICTION, where

- S1:           The speed of vehicle #1,
- S2:           The speed of vehicle #2,
- STIFF1:       The crush stiffness of vehicle #1,
- STIFF2:       The crush stiffness of vehicle #2, and
- FRICTION:    The inter-vehicle friction between vehicle #1 and vehicle #2.

Testing ranges for the impact parameters analysis were

- S1:           19 -- 21 mph,
- S2:           19 -- 21 mph,
- STIFF1:       40 -- 60,
- STIFF2:       40 -- 60, and
- FRICTION:    0.4 -- 0.6.

Post impact coordinate changes collected and analyzed were L1, L2, DH1, and DH2, where

L1: Path length of vehicle #1,

L2: Path length of vehicle #2,

DH1: Heading change of vehicle #1, and

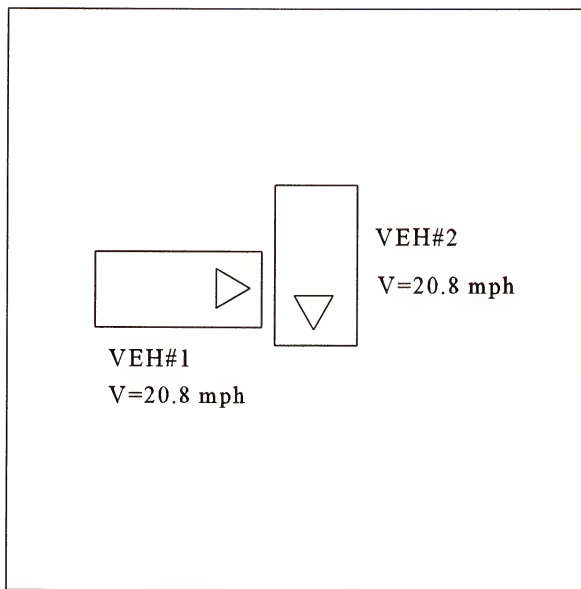
DH2: Heading change of vehicle #2.

The detailed correlation coefficients of the impact parameters analysis are presented as Appendix B.

### Oblique Collision

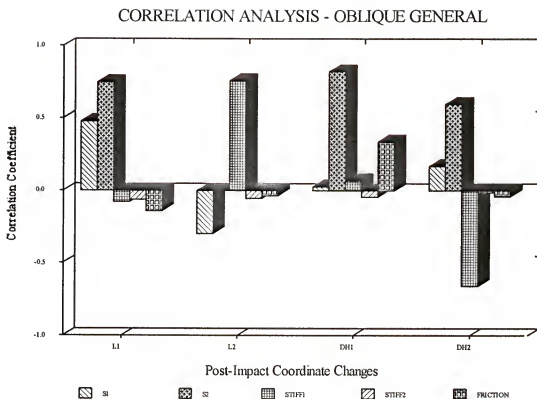
RICSAC test #8 was a right angle, side impact (T-bone) collision. Vehicle #1 struck vehicle #2 with an impact configuration indicated in Figure 3.7. Both vehicles were traveling at a speed of 20.8 mph. The heading angle of vehicle #1 was zero degrees and the heading angle of vehicle #2 was 90 degrees.

The result of the correlation analysis of this particular oblique collision case is presented as Figure 3.8. Both speeds, S1 and S2, had a significant positive effect on L1. All crush parameters, STIFF1, STIFF2, and FRICTION, had a negative effect on L1, but the strength of their influence were not statistically significant. This suggests that the path length of the striking vehicle, L1, was affected mainly by both of the impact speeds and L1 would increase if S1 or S2 increased.



**Figure 3.7** Impact Configuration of RICSAC Test #8

The only positive influential parameter on L2 was STIFF1, which had a very significant effect. S1 also had some effect on L2 but in a negative way. S2, STIFF2, and FRICTION did not have a significant effect on L2. This suggests that in a T-bone collision, the crush stiffness of the striking vehicle, STIFF1, affects the path length of the struck vehicle, L2, considerably and L2 would increase if STIFF1 increased or S1 decreased.



**Figure 3.8** Oblique Collision Correlation Analysis of Speed, Crush Stiffness and Inter-Vehicle Friction

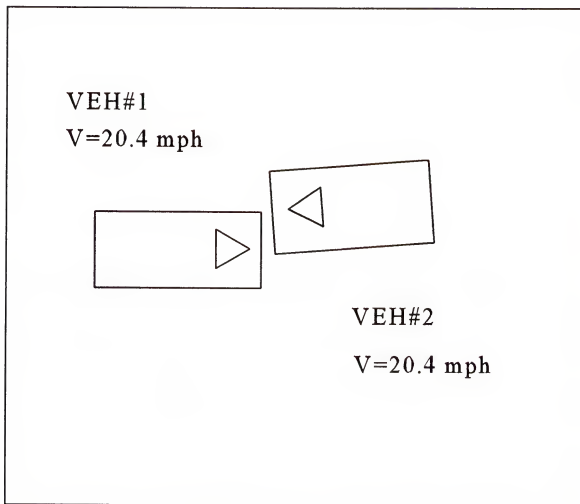
For heading changes, S2 had a major positive effect on DH1, the striking vehicle's heading change. The inter-vehicle friction, FRICTION, also had some positive effect on DH1. This suggests that DH1 would increase if S2 or FRICTION increased. The effect on DH1 of S1, STIFF1, and STIFF2 were not significant.

The heading change of the struck vehicle, DH2, was influenced mainly by STIFF1, S2 and S1. STIFF1 had the most significant negative effect on DH2. S1 and S2, both affected DH2 in a positive way. This suggests that DH2 would increase if STIFF1 decreased or S2

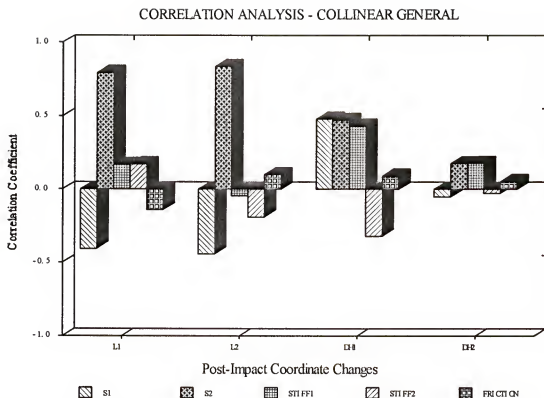
increased or S1 increased. STIFF2 and FRICTION did not have a significant influence on DH2.

#### Collinear Collision

RICSAC test #11 was a head-on collision with an impact configuration as indicated in Figure 3.9. Vehicle #1 was traveling at a speed of 20.4 mph with a heading angle of 171 degrees. Vehicle #2 was also traveling at a speed of 20.4 mph but with a heading angle of zero degrees.



**Figure 3.9** Impact Configuration of RICSAC Test #11



**Figure 3.10** Collinear Collision Correlation Analysis of Impact Speed, Crush Stiffness and Inter-Vehicle Friction

The result of the correlation analysis of the collinear collision is shown as Figure 3.10. For both of the vehicles, path lengths were significantly affected by S1 and S2 but with opposite signs. S1 affected both path lengths negatively and S2 had a more significant positive effect on both path lengths, L1 and L2. This suggests that both L1 and L2 would increase if S2 increased or S1 decreased. This was because vehicle #2 had a greater momentum than vehicle #1 (shown as in Figure C.9). No crush parameters had any significant effect on the path lengths.

With respect to the heading changes, S1, S2, STIFF1, and STIFF2 all had a significant effect on DH1. The signs of the effect of S1, S2, and STIFF1 were positive and the sign for

STIFF2's effect was negative. This implies that DH1 would increase if S1, S2, or STIFF1 increased or STIFF2 decreased. FRICTION's effect on DH1 was not significant.

None of the impact parameters in the test had a significant effect on DH2.

### Summary of Sensitivity Analyses

#### The Effect of Driver Input

1. With the interaction of the speed, steering and wheel forces of a vehicle,
  - (1) Increasing the speed tends to increase the longitudinal, lateral, and heading changes of the vehicle.
  - (2) Increasing the steering tends to decrease the longitudinal changes, yet increase the lateral and heading changes of the vehicle.
2. Among the speed, steering, and wheel forces of a vehicle,
  - (1) The speed of a vehicle has the greatest effect on its longitudinal changes.
  - (2) The front wheel force of the steering side affects the heading changes of the vehicle the most.
3. In balanced braking cases,
  - (1) The speed of a vehicle influences its longitudinal and lateral changes more than the steering does, yet the steering of the vehicle is more dominant than the speed on heading changes.
  - (2) Without the interaction of the steering, the front pair of wheel forces of a vehicle affects its lateral and heading changes less than the rear

pair of wheels, yet affects the longitudinal change more than the rear pair.

### The Effect of Impact Parameters

1. In an oblique collision,
  - (1) Increasing the speed of the striking vehicle tends to increase the path length of the striking vehicle but to decrease the path length of the struck vehicle.
  - (2) Increasing the speed of the struck vehicle tends to increase the path length of the striking vehicle and the heading changes of both vehicles.
  - (3) Increasing the crush stiffness of the striking vehicle tends to increase the path length of the struck vehicle but to decrease the heading change of the struck vehicle.
  - (4) The crush stiffness of the struck vehicle has no significant influence on either the path length or heading change of both vehicles.
  - (5) Increasing the inter-vehicle friction tends to increase the heading change of the striking vehicle but has no other significant effect.
  - (6) The speed of the struck vehicle has the greatest influence on the path length and heading changes of the striking vehicle.
  - (7) The crush stiffness of the striking vehicle affects the path length and heading changes of the struck vehicle more than does the crush stiffness of the struck vehicle.

2. In a collinear collision:

- (1) Increasing the speed of the vehicle which has a smaller mass tends to decrease the path lengths of both vehicles but to increase the larger vehicle's heading change.
- (2) Increasing the speed of the vehicle which has a larger mass tends to increase the path lengths as well as the heading changes of both vehicles.
- (3) Increasing the crush stiffness of the smaller vehicle tends to increase its heading change.
- (4) Increasing the crush stiffness of the larger vehicle tends to decrease the heading change of the smaller vehicle.
- (5) Inter-vehicle friction has no significant effect on both vehicles in a collinear collision.
- (6) The speed of the larger vehicle has the greatest effect on the path lengths of both vehicles.

The findings of the sensitivity analyses are very useful in developing a systematic and efficient approach to converge a simulation result on the actual final rest positions.

## CHAPTER 4

### METHODOLOGY OF ACCIDENT SIMULATION CONVERGENCE

In most accident cases, there is some information or physical evidence missing. For example, the speed and the location of each vehicle at impact, the wheel forces and the steer angle of each vehicle after the impact, the crush stiffness of the sheet metal of each vehicle, the inter-vehicle friction between both vehicles, etc., are usually unknown in most cases. These are the impact parameters which are considered in the accident simulation convergence methodology in this study.

Converging an accident simulation result is similar to searching a simulation result which deviates the least from the actual result. An objective function calculating the path error of each simulation, a blocked coordinate descending search algorithm and a conceptual context of how to build a converging engine for this purpose are presented in this chapter.

#### Objective Function

The goal of this study is to use hill-climbing search algorithm to find a set of input combinations that best converge the simulated final rest positions of the colliding vehicles on their measured final rest positions. For this purpose, a function that can produce values that can be used to evaluate each simulation result is needed.

Since the objective is to determine a set of inputs that makes EDSMAC produce a simulation scenario that has the least path error to the measured final rest positions, Equation

4.1 is formed as the objective function to optimize the convergence results. The path error was defined as the difference between the simulated final rest and the measured final rest.

$$\text{ERROR}_{\text{PATH}} = \text{ERROR}_{\text{RANGE}} + \text{ERROR}_{\text{HEADING}} \quad (4.1)$$

where

$\text{ERROR}_{\text{RANGE}}$  = Range error of X, Y coordinates

$$\text{ERROR}_{\text{RANGE}} = \frac{\Delta(X, Y)}{L_{\text{act}}} \quad (4.2)$$

$\text{ERROR}_{\text{HEADING}}$  = Heading error of the vehicle

$$\text{ERROR}_{\text{HEADING}} = \frac{(\Delta\Psi_{\text{pred}} - \Delta\Psi_{\text{act}})}{360} \quad (4.3)$$

In Equation 4.2, where

$\Delta(X, Y)$  = difference between predicted and measured rest position

$$\Delta(X, Y) = \sqrt{(X_{\text{pred}} - X_{\text{act}})^2 + (Y_{\text{pred}} - Y_{\text{act}})^2} \quad (4.4)$$

$L_{\text{act}}$  = actual path length

$$L_{\text{act}} = \sqrt{(X_{\text{rest}} - X_{\text{imp}})^2 + (Y_{\text{rest}} - Y_{\text{imp}})^2} \quad (4.5)$$

pred = predicted value

act = actual (measured) value

rest = rest coordinate

imp = impact coordinate.

In Equation 4.3, where

$\Delta\Psi_{\text{pred}}$  = predicted heading change

$$\Delta\Psi_{\text{pred}} = (\Psi_{\text{rest}} - \Psi_{\text{imp}})_{\text{pred}} \quad (4.6)$$

$\Delta\Psi_{\text{act}}$  = actual heading change

$$\Delta\Psi_{\text{act}} = (\Psi_{\text{rest}} - \Psi_{\text{imp}})_{\text{act}} \quad (4.7)$$

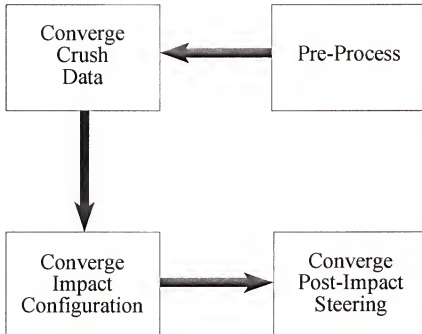
### Contributing Variables Selection

A total of 17 contributing variables related to the aforementioned unknowns were selected. The selection was based mainly on the findings in the previous chapters and the recommendations of accident reconstruction experts. These variables include the crush stiffnesses of vehicles (two variables), the inter-vehicle friction of contracting sheet metal (one variable), the impact speeds of vehicles (two variables), the impact heading angles of vehicles (two variables), the X, Y coordinates of vehicles at impact (four variables), the wheel forces of vehicles at impact (four variables), and the post-impact steering angles of vehicles (two variables).

### Blocked Coordinate Descending Algorithm

If all of the variables were to be used at the same time to generate a search space by using the conventional hill-climbing algorithm, every search space would contain 129,140,163 ( $3^{17}$ ) nodes. Based on the fact that each node would take EDSMAC 20 seconds to generate running on a 486 machine, it would take 82 years just to generate a search space for only one iteration. This is neither feasible nor acceptable for any studies.

To make the convergence feasible and affordable, a blocked coordinates descending (BCD) convergence algorithm has been developed. The theory of a BCD convergence algorithm is to divide a big converging task, in which variables are independent of each other,



**Figure 4.1** Trajectory Convergence Stages Context Diagram

into several smaller converging task blocks. A later block uses the optimized solution derived from its previous block to derive its own local optimization. This process continues until all blocks are converged. For example, in an automobile accident trajectory converging process, the general process can be divided into three stages. Each stage can use a different set of variables to conduct its own stage wise convergence. These three stages (shown as Figure 4.1) are the crush data convergence, the impact configuration convergence, and the post-impact steering convergence.

Since only a few variables are selected to do the convergence at a time, these variables must be very carefully selected and grouped in a way that will not violate the logic in the general converging process. For instance, the post-impact maneuvering convergence task should never be put prior to the impact configuration convergence task, since one may need to go back to do the post-impact maneuvering convergence again after the impact configuration convergence is complete.

The crush data convergence stage contains the variables of inter-vehicle friction and the crush stiffness of each vehicle. The impact configuration convergence stage converges the variables of impact speed, wheel forces, heading angle and the X, Y coordinates at impact of each vehicle. The post-impact steering convergence stage tests the steering angle of each vehicle after the impact.

#### Crush Data Convergence Stage

Three variables need to be converged in this stage. They are the crush stiffness of vehicle #1, the crush stiffness of vehicle #2, and the inter-friction between these two vehicles'

sheet metal. Since these two type of variables are independent, the crush data convergence stage could be further divided into two converging tasks, crush stiffness convergence and inter-vehicle friction convergence, to conduct the convergence of the crush stiffness and the inter-vehicle friction separately. The advantage of doing so is that the size of the search space is reduced from 27 nodes to 12 nodes which surely benefits the speed of convergence.

Inter-vehicle friction convergence task. Only one variable, the inter-vehicle friction between the sheet metal of colliding vehicles, needs to be converged in this task. The size of the search space is three nodes.

Crush stiffness convergence task. Two variables, the crush stiffness of each of the colliding vehicles, need to be converged in this task. The search space contains nine nodes.

#### Impact Configuration Convergence Stage

This stage consists of the converging tasks of impact speeds, wheel forces and impact locations.

Impact speed convergence task. Though speed could be considered a combination of longitudinal speed, lateral speed, and an angular speed, in this study it is assumed that there were no maneuvering behaviors prior to the impact. Therefore, the impact speed is identical with the longitudinal speed. The lateral and angular speeds were assumed to be zero. Since there are only two variables, the search space contains only nine nodes.

Wheel forces convergence task. Though there are four tires for each vehicle, in this study attention is focused on the pair of wheels on the colliding side. The wheels on the non-

colliding side were assumed to retain their initial values throughout the converging process.

There are two reasons for this:

1. The assumption of no damage to the non-colliding side of wheels from the impact. This may not be totally true, but for research purposes this was considered an acceptable limitation of this study.
2. Reduction of the size of the search space. If all eight wheel forces were considered, the search space would have a size of 6,561 nodes and it would take one and a half days to complete only one iteration.

If all the six variables were used in converging the impact locations, the search space would contain 729 nodes which will take a 486 machine more than four hours to generate just a single search space for only one iteration. For efficiency purposes, the impact locations convergence task was further divided into two sub-tasks, the angle of collision convergence and the position of collision convergence, to reduce the size of the search space and speed up the convergence.

Angle of collision convergence task. In the angle of collision convergence, both heading angles of vehicles at impact are converged. The search space has a size of nine nodes.

Position of collision convergence task. In the position of collision convergence, the X and Y coordinates of each vehicle are converged. The search space contains 81 nodes.

#### Post-Impact Maneuvering Convergence Stage

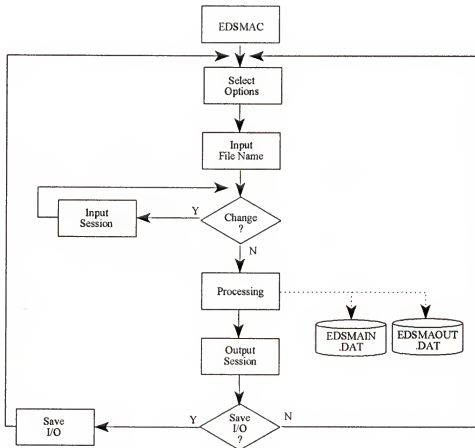
Steering angle convergence task. One more converging stage is added to adjust the final heading angles of both vehicles by testing the after impact steering angles of each

vehicle. The angle of the vehicle's wheel planes may change due to the impact force. The new steering is a function of time which begins at the time of separation.

### Convergence Engine Development

#### Redirect the Control of EDSMAC

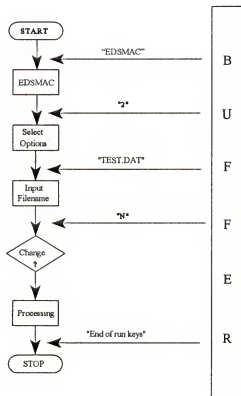
EDSMAC, like the other EDVAP programs, is designed to be executed through a menu driven interface. By going through a few screens, a user can access the initial simulation data and conduct a simulation. This menu driven feature is very user friendly to general users.



**Figure 4.2** Original Control Flow of EDSMAC

However, for those needing to run these programs repeatedly without interruption, this interactive user friendly feature must be eliminated.

To solve this problem, the operating procedure of the program has to be changed. For example, the original operating flow of EDSMAC is shown as Figure 4.2. A user may start by entering "EDSMAC" to call up the two-car collision simulator. To conduct a what-if analysis on an existing file, a user has to select option "2" to retrieve an existing data file containing the necessary information. If there are any changes to be made, the input session of EDSMAC allows the user to do so. Once a user has decided that there are no more changes, EDSMAC saves this final version of the initial conditions to a file named "EDSMAC.DAT" and starts to run the simulation. When the simulation is done, EDSMAC

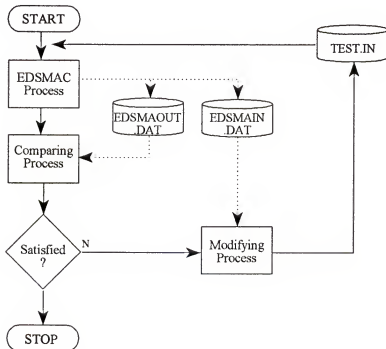


**Figure 4.3** A Modified Control Flow for EDSMAC

saves the result to a file called "EDSMAOUT.DAT" and proceeds to the output session to display the simulation results. At the end of the output session, a user has the choice of whether to save EDSMAIN.DAT or EDSMAOUT.DAT under different names. After that, the control of the program then goes to the first menu again.

The original control flow can be simplified as indicated in Figure 4.3 by skipping the input and output sessions. To do so, a memory buffer is needed to hold all the necessary key strokes and release them at a proper pace and sequence.

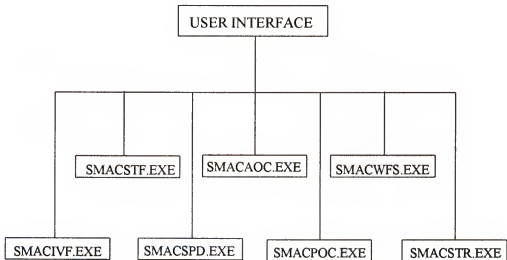
In Figure 4.3, the buffer releases "EDSMAC" and a carriage return key at the DOS prompt to call up EDSMAC. When EDSMAC displays the main menu for job selections, the buffer then releases a "2" to select a re-run option. At this moment, EDSMAC asks for the



**Figure 4.4** A Simulation Control Flow

file name to be retrieved and the buffer feeds this request with "TEST.IN." The process then proceeds to the input session. The buffer gives an answer of "N" to end this session and start simulation. At the end of the simulation, the buffer sends out an "Esc" key and a "6" key to end the process and go back to the DOS prompt.

A controlling program is also needed to perform jobs like running EDSMAC, comparing the simulation results, and modifying the input data file, "TEST.IN." Figure 4.4 shows the simulation control flow. Solid lines represent control flows, dotted lines represent data flows. In the comparison stage, decoded EDSMAOUT.DAT information is compared with the final rest coordinates of both vehicles. In the modifying session, a new set of values

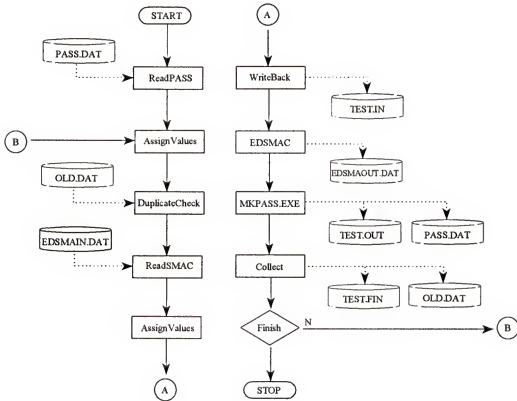


**Figure 4.5** Context Diagram for Convergence Engines

is given to create a new “TEST.IN” file and fed in to EDSMAC to generate a new node in the space.

### Convergence Engine Building

There are seven convergence engines needed to conduct each of the convergence tasks as shown in Figure 4.5. These are SMACIVF, SMACSTF, SMACSPD, SMACAO, SMACPOC, SMACWFS and SMACSTR which converge the inter-vehicle friction, crush stiffness, impact speed, heading angle of collision, position of collision, wheel forces, and steering angles respectively.



**Figure 4.6** The General Flow Chart of Convergence Engines

Each convergence engine is designed to develop its own search space for the use of optimization. Figure 4.6 illustrates the general flow of how an engine works.

ReadPass routine reads the initial information of the convergence from the PASS.DAT file. The PASS.DAT file contains the following information:

- The name of the file where the measured final rest positions of the testing case are stored.
- The objective function which calculates path errors.
- The name of the converging task.
- The current number of iterations.
- The step width for the current iteration.
- Testing values for the current simulation.

The AssignValues routine assigns different combinations of testing values for each testing node. Different step widths are given based on the on-going converging task.

The DuplicateCheck routine reads converging history from the OLD.DAT file and checks for duplicates. A hill-climbing search tends to step back and forth in search of a better spot. It is not unusual for some spots to be stepped more than once in different iterations. If a node that has been stepped before is not a better spot, there is no need to waste time running a simulation using the information of that node again, since the objective function value of this node has already been computed, compared and discarded. DuplicateCheck routine checks the combination given by AssignValues routine. The OLD.DAT file keeps track of the nodes that have been simulated. If a new given combination exists in OLD.DAT, the combination is skipped and a new combination is assigned.

ReadSMAC and WriteBack routines work together to create a new TEST.IN file for EDSMAC simulations. The ReadSMAC routine reads the previous EDSMAC running information from EDSMAIN.DAT. The WriteBack routine substitutes the converging variables in EDSMAIN.DAT with the new values given by the AssignValues routine and makes the TEST.IN file the new input file for the EDSMAC program. EDSMAC is then called to run the simulation with the contents of TEST.IN and saves the result in EDSMAOUT.DAT

The MKPASS sub-program reads the EDSMAOUT.DAT file to generate TEST.DAT which contains the information of the heading angles, X, Y coordinates of both vehicles at the stages of the initial, impact, separate, and final rest. MKPASS also saves the current converging combinations in PASS.DAT for the use of the next simulation.

The Collect routine appends TEST.OUT to TEST.FIN to create the search space of the iteration. A search space is completed if all eligible combinations have been given and simulated. After all eligible combinations are tested, the BCD task is done.

#### Step Width of Each Converging Task

The conventional hill-climbing algorithm has the recognized drawbacks of foothill, plateau, and ridge problems. To minimize these, each BCD is designed to conduct its local convergence in three different levels by using three different step widths each smaller than the other. Table 4.1 shows the step width in each of the BCDs.

At level 1, a BCD uses a wider step width conducting the convergence and finding its local optimum. When the best node in the first level is found, the BCD uses one half of the

**Table 4.1** Step Widths in Different Levels at Each Converging Task

TASK	LEVEL1	LEVEL 2	LEVEL 3
IVF	0.10	0.05	0.01
STF	10.00	5.00	1.00
SPD(mph)	1.00	0.50	0.10
WFS	-0.10	-0.05	-0.01
AOC(deg)	10.00	5.00	1.00
POC(ft)	1.00	0.50	0.10
STR(deg)	10.00	5.00	1.00

previous step width to conduct the second level convergence around the first level optimum. After the second level optimum is found, the BCD then uses one fifth of the second level step width to conduct the third level convergence around the second level optimum. Thus, the chances of falling into the drawbacks of the conventional hill-climbing algorithm are effectively minimized.

#### Automatic Coordinate Converging System Implementation

An Automatic Coordinate Converging System (ACCS) program is developed to serve as a user interface to conduct the automatic converging task. By typing "ACCS" at the DOS prompt, the system asks the user to feed in the impact and final rest coordinates of both vehicles (shown as Figures 4.7 -- 4.8 where underlined values are user inputs).

```
*****
* Automatic Coordinate Converging System *
*****

Please type in the IMPACT coordinates of Vehicle #1:

X coordinate? -10.8
Y coordinate? 1
H coordinate? -30

Please type in the IMPACT coordinates of Vehicle #2:

X coordinate? 0
Y coordinate? -5.5
H coordinate? 90
```

**Figure 4.7** ACCS Input Session Screen 1

```
*****
* Automatic Coordinate Converging System *
*****

Please type in the FINAL REST of Vehicle #1:

X coordinate? -1
Y coordinate? 5.4
H coordinate? -1.5

Please type in the FINAL REST of Vehicle #2:

X coordinate? 8.5
Y coordinate? 7.8
H coordinate? 105
```

**Figure 4.8** ACCS Input Session Screen 2

After the impact and final rest coordinates of both vehicles are input, ACCS provides a recommended converging sequence, as shown in Figure 4.9, and asks whether the user wants to change it. If the user answers this question "No," ACCS then starts the converging process with the default sequence.

```

*****
* Automatic Coordinate Converging System *
*****

The default order of convergence is:

ivf stf wfs spd aoc poc str

Do you want to change the order? (Y/N)? n

```

**Figure 4.9** ACCS Input Session Screen 3

If the user answers the question in Figure 4.9 "Yes," ACCS then asks the user to give his/her preferred order of each converging task to form a new converging sequence. ACCS shows the new converging sequence and asks the user if he/she wants to change the order or not. If the answer is "Yes," the prioritizing process of reforming a new converging sequence repeats. If the answer is "No," the converging process begins with the new converging sequence (shown as Figures 4.10 -- 4.12).

```

*****
* Automatic Coordinate Converging System *
*****

The default order of convergence is:

      ivf stf wfs spd aoc poc str

Do you want to change the order? (Y/N)? y

```

**Figure 4.10** ACCS Input Session Screen 4

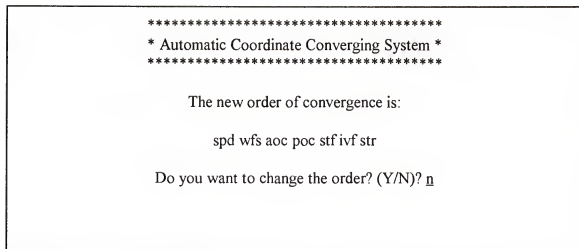
```

*****
* Automatic Coordinate Converging System *
*****

In what order you want to converge IVF? 6
In what order you want to converge STF? 5
In what order you want to converge WFS? 2
In what order you want to converge SPD? 1
In what order you want to converge AOC? 3
In what order you want to converge POC? 4
In what order you want to converge STR? 7

```

**Figure 4.11** ACCS Input Session Screen 5



**Figure 4.12** ACCS Input Session Screen 6

After the converging process begins, ACCS calls up the EDSMAC program and gives minimum necessary keystrokes from a memory buffer to mimic the response EDSMAC expected from a human user. In Figure 4.13, the memory buffer sent a keystroke of "2" and a string of "TEST.IN" to the first EDSMAC user interactive screen to direct EDSMAC running a simulation using the initial pre-impact information stored in the TEST.IN file. After the TEST.IN file was retrieved, ACCS sent a "No" answer to the question in Figure 4.14 to start the collision simulation.

## ENGINEERING DYNAMICS CORPORATION

## EDSMAC

Copyright 1993

Version: 2.51 User No: 0673-0

Licensed User: J. Wattleworth &amp; Assocs.

Program Menu:

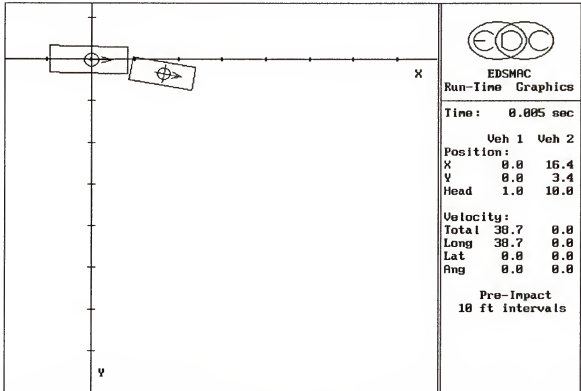
1. First-run, interactive session
2. Rerun with input from a previous session
3. Output from a previous session
4. Graphics
5. Exit to Main Menu
6. Exit to DOS

Select menu number (1-6): 2

Filename? (or &lt;RETURN&gt;): C:\RICH\EDVAP\TEST.IN

**Figure 4.13** EDSMAC Input Session Screen 1Any changes (Y or N)?n**Figure 4.14** EDSMAC Input Session Screen 2

The EDSMAC graphical simulation process displays the collision in an animated fashion. Figures 4.15 - 4.18 represent four of the animation frames at three different collision phases, namely pre-impact, impact and post-impact phases, and the final rest.



**Figure 4.15** EDSMAC Graphical Output -- Pre-Impact Phase

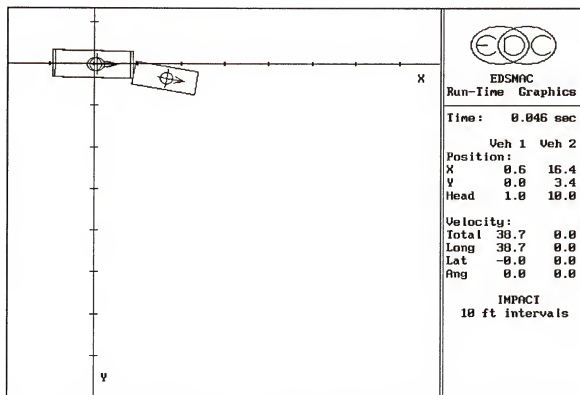
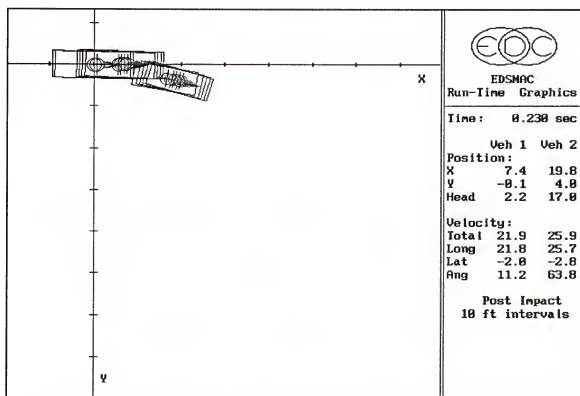
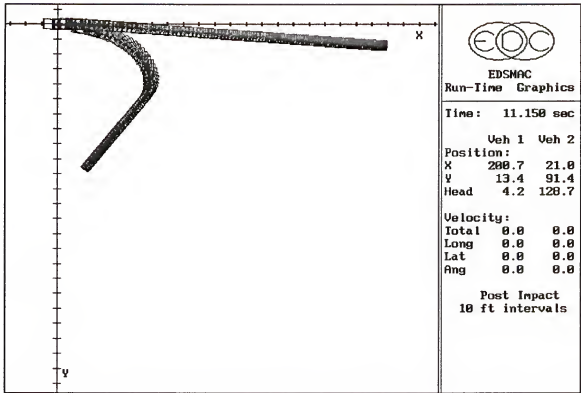


Figure 4.16 EDSMAC Graphical Output -- Impact Phase

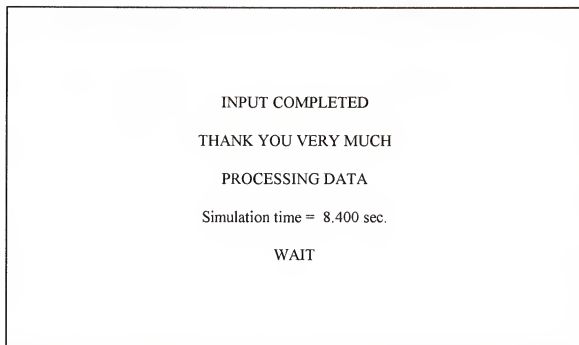


**Figure 4.17** EDSMAC Graphical Output -- Post-Impact Phase

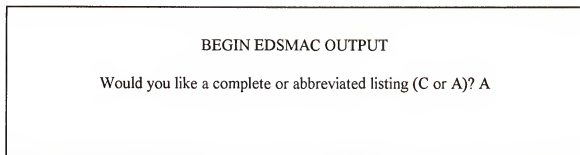


**Figure 4.18** EDSMAC Graphical Output -- Final Rest Positions

The purpose of running EDSMAC in ACCS is to generate a search space for searching the local optimum. The graphical animation feature in the EDSMAC program is very useful for a human expert to visually compare the simulation result. However, for a self-iterative system like the ACCS, this feature needs to be eliminated to minimize the time needed to generate a search space. Figure 4.19 is the text mode of the simulation session of the EDSMAC program. When EDSMAC finished a simulation, it prompted a question as Figure 4.21, ACCS then responded with an "Esc" key to skip the control flow of EDSMAC to the first screen as Figure 4.13 and sent a "6" key to terminate the execution of EDSMAC and return the control to the ACCS.



**Figure 4.19** A Screen of the Simulation Processing Session of EDSMAC(Text Mode)



**Figure 4.20** A Screen of the Output Session of EDSMAC

## CHAPTER 5

### EVALUATION OF ACCIDENT SIMULATION CONVERGENCE

The impact configurations and final rest positions of the RICSAC staged collision cases were used to evaluate the performance of the blocked coordinate descending (BCD) convergence algorithm. These parameters were used because they are documented and assumed to be accurate.

Due to some problems which occurred during the conduct of RICSAC test #5 and #10, they were not used in this study. Thus, only the information of the ten of the twelve RICSAC tests were used to serve the evaluation purpose.

Table 5.1 shows the impact speeds, the impact configurations, and the final rest positions of the ten usable RICSAC staged crash tests. Cases of tests 1, 2, 6, 7, 8, and 9 were oblique collisions while tests 3 and 4 were 90-degree T-bone collisions. Cases of tests 3, 4, 11, and 12 were collinear collisions where tests 3 and 4 were rear-end and tests 11 and 12 were head-on collisions.

#### RICSAC Simulation Results without Optimization

Ten collision simulations using the impact speed and the impact configuration information of RICSAC tests were conducted. Other information such as crash data used the EDSMAC defaults. Post-impact steerings were neglected. The results of these ten unoptimized simulations and their path errors, which were calculated by using Equation 4.1

**Table 5.1** Impact/Rest Positions of 10 Usable RICSAC Staged Crash Tests

RICSAC TEST	IMPACT SPEED (mph)	IMPACT POSITION			REST POSITION		
		X (ft)	Y (ft)	PSI (deg)	X (ft)	Y (ft)	PSI (deg)
1 (Oblique)	19.8	-10.9	1.9	-30.0	11.0	5.4	-1.5
	19.8	0.0	-5.5	90.0	8.5	7.8	105.0
2 (Oblique)	31.5	-11.2	8.5	-30.0	11.0	5.4	55.0
	31.5	0.0	0.0	90.0	23.6	12.5	134.0
4 (Collinear)	21.0	0.0	0.0	0.0	111.4	2.0	-4.0
	0.0	15.0	2.2	10.0	181.5	-6.3	-19.0
4 (Collinear)	38.7	0.0	0.0	1.0	42.8	54.5	137.5
	0.0	16.4	3.4	10.0	63.5	62.5	88.0
8 (Oblique)	21.5	0.0	0.0	0.0	60.0	11.0	15.0
	21.5	11.1	2.7	120.0	20.0	21.0	242.0
7 (Oblique)	20.8	0.0	0.0	0.0	84.5	18.2	16.5
	20.8	10.7	3.5	120.0	22.9	41.4	262.0
8 (Oblique)	20.8	-10.9	3.2	0.0	0.0	10.8	45.0
	20.8	0.0	1.9	90.0	6.3	18.2	134.0
9 (Oblique)	21.2	0.0	0.0	0.0	4.0	35.5	104.0
	21.2	8.5	-5.9	90.0	-5.0	49.5	152.0
11 (Collinear)	20.4	15.7	-4.0	171.0	25.6	-6.4	170.0
	20.4	0.0	0.0	0.0	8.6	0.4	0.0
12 (Collinear)	31.5	15.7	-4.0	171.0	22.3	-5.5	118.0
	31.5	0.0	0.0	0.0	6.8	2.6	-12.0

Table 5.2 Final Rest Positions without Optimization

RICSAC TEST	METHOD	REST POSITION					
		VEH #1			VEH #2		
		X (ft)	Y (ft)	PSI (deg)	X (ft)	Y (ft)	PSI (deg)
1	Measured	11.00	5.40	-1.50	8.50	7.80	105.00
	Simulated	2.62	-1.70	-4.00	9.13	5.21	120.21
2	Measured	11.00	9.40	55.00	23.60	12.50	134.00
	Simulated	5.66	7.29	69.96	47.59	15.18	178.21
4	Measured	111.40	2.00	-4.00	181.50	-6.30	-19.00
	Simulated	96.05	-0.41	-2.07	208.21	52.15	14.66
4	Measured	42.80	54.50	137.50	63.50	62.50	88.00
	Simulated	206.12	25.76	7.82	54.52	23.12	190.21
3	Measured	60.00	11.00	45.00	20.00	21.00	242.00
	Simulated	68.39	9.23	8.36	12.21	46.13	265.06
4	Measured	84.50	18.20	16.50	22.90	41.40	262.00
	Simulated	206.08	28.74	8.02	3.11	40.32	451.52
8	Measured	0.00	10.80	45.00	6.30	19.20	130.00
	Simulated	14.81	18.15	30.51	-8.83	35.35	142.46
9	Measured	4.00	35.50	104.00	-5.00	49.50	152.00
	Simulated	8.25	28.06	82.87	53.71	98.03	66.46
11	Measured	25.60	-6.40	170.00	8.60	0.40	0.00
	Simulated	50.49	-18.48	158.67	7.52	0.93	4.17
12	Measured	22.30	-5.50	118.00	6.80	2.60	-12.00
	Simulated	23.13	-10.32	148.88	15.31	-0.56	-16.11

Table 5.3 Path Errors without Optimization

RICSAC TEST	PATH ERROR							
	VEH #1				VEH #2			
	RANGE (ft) (%)		HEADING (deg) (%)		RANGE (ft) (%)		HEADING (deg) (%)	
1	7.97	58.21	2.59	0.72	2.67	18.94	15.21	4.22
2	5.74	33.97	14.96	4.16	24.14	48.33	44.21	12.28
3	15.54	16.18	1.93	0.54	64.26	32.20	33.66	9.35
4	165.83	80.05	129.68	36.02	40.39	94.11	102.21	28.39
5	8.57	12.43	6.64	1.84	26.31	60.57	23.06	6.41
7	122.04	58.65	8.48	2.36	19.82	52.73	189.52	52.64
8	16.53	55.59	14.49	4.02	22.13	63.98	12.46	3.46
9	8.57	29.29	21.13	5.87	76.17	67.21	85.54	23.76
11	27.67	72.86	11.33	3.15	1.20	16.53	4.17	1.16
12	4.89	48.19	30.88	8.58	9.08	61.09	4.11	1.14
Avg.	38.34	46.54	24.21	6.73	28.62	51.57	51.42	14.28
Std.	57.00	22.91	38.07	10.57	24.99	23.71	58.96	16.38

( $ERROR_{PATH} = ERROR_{RANGE} + ERROR_{HEADING}$ ), are listed as Tables 5.2 and 5.3.

The unoptimized average range error and heading error of simulation results from actual final rest positions for vehicle #1 was 46.54% and 6.73% with standard deviations of 22.91 feet and 10.57 feet respectively. The unoptimized average range error and heading error for vehicle #2 was 51.57% and 14.28% with standard deviations of 23.71 degrees and 16.38 degrees respectively.

### RICSAC Simulation Results with Optimization

#### Converging Sequence

The optimized result is very sensitive to the converging sequence in the automatic coordinate converging system (ACCS). ACCS may produce a different optimized simulation scenario if a different converging sequence is adopted.

Four different combinations of the sequences of the seven converging tasks were arranged (shown as Table 5.4) and conducted to compare the performance of different converging sequences. The converging tasks represented by notations in Table 5.4 are:

- IVF: Inter-vehicle friction convergence,
- STF: Crush stiffness convergence,
- WFS: Wheel forces convergence,
- AOC: Angle of collision convergence,
- POC: Position of collision convergence,
- SPD: Impact speed convergence, and
- STR: Post-impact steering convergence.

Crush data is converged first in sequence combinations A through C, the inter-vehicle friction prior to the crush stiffness. Post-impact steering is the last converging task in all sequence combinations.

Sequence combination A is designed for RICSAC tests specifically. Since impact speeds of RICSAC tests were assumed as known data, the impact speed (SPD) convergence is placed after the impact configuration (AOC and POC) convergence to minimize the

**Table 5.4** Converging Sequences for Testing Combinations

Converging Tasks	Combinations for Converging Task Sequences			
	A	B	C	D
1	IVF	IVF	IVF	SPD
2	STF	STF	STF	WFS
3	WFS	SPD	WFS	AOC
4	AOC	WFS	SPD	POC
5	POC	AOC	AOC	STF
6	SPD	POC	POC	IVF
7	STR	STR	STR	STR

possible range of impact speeds.

The design of sequence combinations B and C is based on the fact that impact speeds are the major contributing variables in accident trajectory simulations. The sequence of the convergence tasks of wheel forces (WFS) and impact speeds (SPD) is switched in sequence combinations B and C to see which would generate better results.

The design of sequence combination D is based on the recommendation of accident reconstruction experts. In the process of reconstructing an accident, a reconstructionist is most concerned with how fast both vehicles were traveling at the moment of impact. The second issue which interests a reconstructionist is where did these two vehicles collided. Since wheel forces have a direct contribution to speed, WFS was put right behind SPD and prior to AOC and POC in the convergence sequence. Crush data and post-impact steering are used to fine tune the results in this sequence combination.

### Optimized Path Errors of Different Converging Sequences

The results of the ACCS program using converging sequences A, B, C, and D are listed as Tables 5.5 through 5.8. In Table 5.5, ACCS used converging sequence A to converge the RICSAC cases. Among these ten cases, tests 1, 3, 6, and 8 met the 10% threshold (used by Day and Hargens [19] to classify a good simulation result) for range and heading errors of both vehicles. ACCS using converging sequence B converged tests 1, 3, 4, 6, and 9 to meet the 10% threshold (shown as Table 5.6). In Table 5.7, tests 1, 3, 6, and 8 were converged meeting the 10% threshold again by ACCS using converging sequence C. In Table 5.8, ACCS using converging sequence D converged tests 2, 3, 4, 6, and 11 to meet the 10% threshold.

**Table 5.5 Path Errors of Converging Sequence A**

RICSAC Test	Converging Sequence A				
	Veh#1		Veh#2		Sum
	Range	Heading	Range	Heading	
1	8.17%	2.60%	1.06%	0.26%	20.03%
2	1.29%	22.41%	0.62%	0.46%	24.78%
4	0.65%	9.65%	1.57%	0.48%	12.35%
4	15.54%	2.04%	6.68%	0.26%	24.52%
6	2.24%	0.31%	0.16%	2.14%	4.85%
7	1.53%	42.37%	0.84%	4.59%	49.33%
8	0.60%	3.21%	1.29%	0.18%	5.28%
9	19.68%	1.73%	0.78%	8.16%	30.35%
11	19.33%	1.43%	0.13%	0.05%	20.94%
12	28.96%	0.99%	8.90%	0.28%	39.13%

Table 5.6 Path Errors of Converging Sequence B

RICSAC Test	Converging Sequence B				
	Veh#1		Veh#2		Sum
	Range	Heading	Range	Heading	
4	8.17%	2.60%	1.06%	8.20%	20.03%
2	0.21%	15.31%	3.23%	0.31%	19.06%
3	0.06%	1.99%	1.46%	3.99%	7.50%
4	5.87%	3.43%	5.42%	0.70%	15.42%
6	2.71%	0.13%	0.13%	0.25%	3.23%
7	3.46%	44.66%	0.64%	0.56%	49.32%
8	0.17%	13.88%	5.01%	1.16%	20.22%
9	2.89%	3.91%	2.02%	0.19%	9.01%
11	15.00%	0.55%	0.08%	0.25%	15.88%
12	33.24%	1.59%	4.30%	7.05%	46.18%

Table 5.7 Path Errors of Converging Sequence C

RICSAC Test	Converging Sequence C				
	Veh#1		Veh#2		Sum
	Range	Heading	Range	Heading	
1	8.17%	2.60%	1.06%	8.26%	20.03%
2	1.29%	22.41%	0.62%	0.46%	24.78%
4	9.65%	9.65%	1.57%	0.46%	12.35%
4	15.54%	2.04%	6.68%	0.26%	24.52%
6	3.77%	0.24%	1.39%	1.13%	6.53%
7	1.53%	42.37%	0.84%	4.59%	49.33%
8	0.24%	1.87%	0.96%	2.97%	6.04%
9	2.32%	16.26%	1.96%	1.71%	22.25%
11	20.07%	2.06%	0.36%	0.15%	22.65%
12	29.01%	0.83%	10.25%	0.44%	40.53%

**Table 5.8** Path Errors of Converging Sequence D

RICSAC Test	Converging Sequence D				
	Veh#1		Veh#2		Sum
	Range	Heading	Range	Heading	
1	0.48%	22.32%	0.43%	6.14%	29.34%
2	0.23%	6.70%	0.74%	1.43%	9.10%
3	0.02%	0.11%	1.53%	3.65%	5.31%
4	5.21%	0.06%	4.78%	2.82%	12.87%
6	3.34%	0.25%	0.02%	2.29%	5.90%
7	7.60%	13.83%	0.00%	0.22%	21.65%
8	0.12%	15.31%	1.04%	0.12%	16.59%
9	0.92%	30.02%	3.27%	9.35%	43.55%
11	9.41%	0.79%	0.12%	0.93%	11.24%
12	12.58%	0.53%	0.71%	1.20%	15.02%

The optimized objective function values (the sum of the range and heading errors of both vehicles) of these four sequence combinations are listed as Table 5.9. In Table 5.9, the ten best objective function values for each of the respective RICSAC cases are highlighted. The EDSMAC input data set of these ten optimized scenarios are presented as Appendix C. All collinear collisions (tests 3, 4, 11, and 12) and two oblique collisions (tests 2 and 7) were best converged by using converging sequence D. There is no difference among combinations A, B, and C on test no. 1. Converging sequences A and C produced identical convergence results in tests 1, 2, 3, 4, and 7. This implies that it does not matter if the order of the impact speed convergence is put before or after the impact configuration convergence as long as they are placed after the converging task of wheel forces (WFS). However, the fact that converging sequence B better converged the final rest positions of these ten cases than

**Table 5.9** Optimized Objective Function Values for Various Converging Methods

RICSAC TEST	CONVERGING SEQUENCES			
	A	B	C	D
4	20.03	20.03	20.03	29.34
2	24.78	19.06	24.78	9.10
8	12.35	7.50	12.35	5.31
4	24.52	15.42	24.52	12.87
4	4.85	3.23	6.04	5.90
4	49.33	49.32	49.33	21.65
8	5.28	20.22	6.04	16.59
9	30.35	9.01	22.25	43.55
11	20.94	15.88	22.65	11.24
12	39.13	46.18	40.53	15.02
Avg.	23.16	20.59	22.90	17.06
Std.	14.07	15.42	13.69	11.81

sequence A and C, and that converging sequence D converged the final rest positions better than the other converging sequence combinations proves that the simulation result is more sensitive to impact speeds than other factors.

The optimized final rest positions of these ten RICSAC cases are listed as Table 5.10. Their path errors are listed as Table 5.11. All of the heading errors of both vehicles are less than 10%. All range errors also fall within the 10% range except vehicle #1 in Case #12 and vehicle #2 in case #7 in which their range errors are a little over the 10% level (12.57% and

Table 5.10 Final Rests after Optimization

RICSAC TEST	METHOD	REST POSITION					
		VEH #1			VEH #2		
		X (ft)	Y (ft)	PSI (deg)	X (ft)	Y (ft)	PSI (deg)
1	Measured	-1.00	5.40	-1.50	8.50	7.80	105.00
	Optimized	-1.56	6.33	2.32	8.97	7.93	75.48
2	Measured	11.00	9.40	55.00	23.60	12.50	130.00
	Optimized	10.95	9.41	52.33	25.46	12.72	128.85
3	Measured	111.40	2.00	-4.00	181.50	-6.30	-19.00
	Optimized	111.41	1.99	1.51	181.64	-6.43	-5.87
4	Measured	42.80	54.50	137.50	63.50	62.50	88.00
	Optimized	43.74	51.22	120.28	63.53	62.53	77.85
5	Measured	60.00	11.00	15.00	20.00	21.00	242.00
	Optimized	60.19	12.58	15.51	19.97	21.01	241.11
7	Measured	84.50	18.20	16.50	22.90	41.40	262.00
	Optimized	78.72	18.50	16.49	21.67	47.73	262.78
8	Measured	0.00	10.80	45.00	6.30	19.20	130.00
	Optimized	0.08	10.82	40.37	6.49	19.79	129.35
9	Measured	0.00	35.50	104.00	-5.00	49.50	152.00
	Optimized	3.37	34.72	96.73	-6.17	51.50	151.31
11	Measured	25.60	-6.40	170.00	8.60	0.40	0.00
	Optimized	25.07	-7.20	169.58	8.58	0.46	-3.34
12	Measured	22.30	-5.50	118.00	6.80	2.60	-12.00
	Optimized	21.68	-6.23	120.54	6.78	2.63	-7.67

Table 5.11 Path Errors after Optimization

RICSAC TEST	PATH ERROR							
	VEH #1				VEH #2			
	RANGE		HEADING		RANGE		HEADING	
	(ft)	(%)	(deg)	(%)	(ft)	(%)	(deg)	(%)
1	1.09	8.14	3.82	1.06	0.49	2.61	29.52	8.20
2	0.05	0.24	2.67	7.42	1.87	6.70	5.15	1.43
3	0.01	0.01	5.51	1.53	0.19	0.11	13.13	3.65
4	3.41	5.22	17.22	4.78	0.04	0.06	10.15	2.82
5	1.09	2.70	0.01	0.14	0.03	0.15	0.89	0.25
6	5.79	7.60	0.01	0.00	0.49	13.82	0.78	0.22
8	0.01	0.62	4.63	1.29	0.62	3.21	0.65	0.18
9	1.00	2.87	7.27	2.02	2.32	3.91	0.69	0.19
11	0.96	9.44	0.42	0.12	0.06	0.81	3.34	0.93
12	0.96	12.57	2.54	0.71	0.04	0.55	4.33	1.20
Avg.	1.49	4.94	4.46	1.91	1.21	3.19	6.86	1.91
Std.	1.71	4.13	4.80	2.26	1.91	4.09	8.57	2.38

13.82% respectively).

The average range error and heading error of vehicle #1 is 4.94% and 1.91% with standard deviations of 4.13 and 2.26 degrees. The average range error and heading error of vehicle #2 is 3.19% and 1.91% with standard deviations of 4.09 and 2.38 degrees. The average offset of final rest positions for vehicle #1 and #2 is 1.49 feet and 1.21 feet. The average offset of final rest heading angles of vehicle #1 and #2 is 4.46 degrees and 6.86 degrees.

The reduction of path errors through use of optimization is very significant. The average range offset of final positions for vehicle #1 reduced from 38.34 feet to 1.49 feet. The average range offset of final positions for vehicle #2 reduced from 28.62 feet to 1.21 feet. The reduction in average range offset of final positions was 96.11% for vehicle #1 and 95.77% for vehicle #2. The average heading offset for vehicle #1 reduced from 24.21 degrees to 4.46 degrees. The average heading offset for vehicle #2 reduced from 51.42 degrees to 6.86 degrees. The reduction in heading offset was 81.58% for vehicle #1 and 86.66% for vehicle #2. The path errors of vehicle #1 were reduced from 46.54% to 4.94% on the range error and from 6.73% to 1.91% on the heading error. In vehicle #2, the range error was reduced from 51.57% to 3.19% and the heading error was reduced from 14.28% to 1.91%.

### Impact Configuration Errors

The improvement of BCD convergence results of these ten RICSAC cases was achieved mainly by justifying their impact speeds and configurations. Tables 5.12 through 5.14 show the impact speed, impact configuration, and the errors of optimized results.

In Table 5.12, the average error of impact speed of vehicle #1 and #2 is 2.08 mph and 2.92 mph respectively. Converged impact speeds, in tests 2, 3, 7, and 12, which have an error greater than 2 mph from RICSAC testing speeds were all produced by using sequence combination D to achieve convergence. This is because impact speeds were placed as the first converging task in the sequence. As the first set of factors in a converging task sequence, impact speed has the greatest freedom of justification of value, hence, it has a higher chance to generate a greater range of errors. For the same reason, tests 1 and 8 have the least impact

speed offset due to the fact that the impact speed converging task (SPD) was placed last in the impact configuration convergence.

**Table 5.12 BCD Optimized Impact Speed Errors**

RICSAC TEST	IMPACT SPEED ERROR					
	VEH #1			VEH #2		
	RICSAC	Optimized	ERROR	RICSAC	Optimized	ERROR
1	19.80	19.80	0.00	19.80	19.80	0.00
2	31.50	33.50	2.00	31.50	27.00	4.50
3	21.40	17.00	4.00	0.00	7.00	7.00
4	37.70	37.70	1.00	0.00	1.00	1.10
6	21.50	22.00	0.50	21.50	19.50	2.00
7	29.10	21.40	8.00	29.10	22.00	7.10
8	20.80	20.90	0.10	20.80	20.70	0.10
9	21.20	20.70	0.50	21.20	22.10	0.90
11	20.40	21.40	1.00	20.40	21.20	0.80
12	31.50	27.80	3.70	31.50	25.80	5.70
Avg.	2.08			2.92		
Std.	2.52			2.86		

Tables 5.13 and 5.14 show BCD optimized impact configurations and their deviation from RICSAC tests. The average error of impact positions of vehicle #1 and #2 is 1.89 feet and 2.47 feet respectively. The error of impact heading angles of vehicle #1 and #2 is 0.40 degrees and 2.80 degrees respectively.

Table 5.13 BCD Optimized Impact Configuration

RICSAC TEST	IMPACT CONFIGURATION						
	METHOD	VEH #1			VEH #2		
		(ft)		(deg)	(ft)		(deg)
1	RICSAC	-10.90	1.00	-30.00	0.00	-5.90	90.00
	Optimized	-10.90	6.20	-30.00	16.40	-2.70	90.00
2	RICSAC	-11.20	8.50	-30.00	0.00	0.00	90.00
	Optimized	-10.90	8.40	-30.00	3.50	0.10	89.00
3	RICSAC	0.00	0.00	0.00	15.00	2.20	10.00
	Optimized	0.30	-0.70	1.00	15.20	1.70	0.00
4	RICSAC	0.00	0.00	1.00	16.40	3.40	10.00
	Optimized	2.80	-0.20	1.00	19.20	3.20	10.00
5	RICSAC	0.00	0.00	0.00	11.10	2.70	120.00
	Optimized	1.10	-1.90	0.00	14.20	-0.20	119.00
7	RICSAC	0.00	0.00	0.00	10.70	3.50	120.00
	Optimized	3.30	-1.00	0.00	16.90	-0.50	105.00
8	RICSAC	-10.90	3.20	0.00	0.00	1.90	90.00
	Optimized	-10.90	3.00	2.00	-0.20	1.70	91.00
9	RICSAC	0.00	0.00	0.00	8.50	-5.90	90.00
	Optimized	0.00	0.00	0.00	8.50	-5.90	90.00
11	RICSAC	15.70	-4.00	171.00	0.00	0.00	0.00
	Optimized	16.10	-3.90	172.00	0.20	0.00	0.00
12	RICSAC	15.70	-4.00	171.00	0.00	0.00	0.00
	Optimized	15.60	-2.30	171.00	-0.10	1.70	0.00

Table 5.14 BCD Optimized Impact Configuration Errors

RICSAC TEST	IMPACT CONFIGURATION ERROR			
	VEH #1		VEH #2	
	RANGE	HEADING	RANGE	HEADING
1	0.00	0.00	6.99	0.00
2	0.61	0.00	0.54	0.00
4	0.76	1.00	0.54	15.00
4	2.81	0.00	2.81	0.00
6	2.20	0.00	4.25	1.00
4	3.45	0.00	7.38	15.00
6	0.36	2.00	0.28	1.00
4	0.00	0.00	0.00	0.00
11	2.21	1.00	2.20	0.00
12	1.70	0.00	1.70	0.00
Avg	1.89	0.40	2.47	2.80
Std	2.02	0.70	2.83	5.27

For range errors, six out of the ten cases (tests 2, 3, 8, 9, 11, and 12) fall within a two-foot error range where four were converged by using converging sequence D (tests 2, 3, 11, and 12), and two were converged by using converging sequence A (test 8) and B (test 9). For impact heading errors, eight out of the ten cases (tests 1, 2, 4, 6, 8, 9, 11, and 12) fall within a five-degree error range. The heading errors of vehicle #1 in all tests were within a two degree error range. The heading errors of vehicle #2 were also within the two-degree range except in tests 2, 3, and 7.

## CHAPTER 6

### CONCLUSIONS AND RECOMMENDATIONS

This dissertation has demonstrated that the performance of converging EDSMAC's simulation results with RICSAC staged collisions can be effectively and efficiently improved by using a blocked coordinate descending (BCD) convergence algorithm. An automatic coordinate converging system was developed in this study to implement the BCD convergence algorithm to conduct the convergence. When this was done, the results for both vehicles achieved more than a 95% reduction of range offsets and more than a 80% reduction of heading offsets compared to the unoptimized results..

A large task like converging an accident scenario should be divided into several smaller BCD tasks. However, before the BCD algorithm can be applied to reproduce the scenario of a general accident case with a simulator, the contributing factors to the simulator must be analyzed. Also, each of the BCD converging tasks should be carefully arranged in an order that does not violate the sequence of events of the accident. The conclusions and recommendations listed below are offered as the results of the study.

## Conclusions

### Relative Effects of Contributing Factors in Accident Simulations

EDSVS (a single vehicle maneuvering simulator) and EDSMAC (a two-car collision simulator) were used to conduct the sensitivity analyses of how a driver's input affects the traveling path of a vehicle and how impact forces affect the vehicles involved in an accident.

### The effect of driver's input

1. With the interaction of the speed, steering, and wheel forces of a vehicle,
  - (1) Increasing the speed tends to increase the longitudinal, lateral, and heading changes of the vehicle.
  - (2) Increasing the steering tends to decrease the longitudinal changes, yet increase the lateral and heading changes of the vehicle.
2. Among the speed, steering, and wheel forces of a vehicle,
  - (1) The speed of a vehicle has the greatest effect on its longitudinal changes.
  - (2) The front wheel force of the steering side affects the heading changes of the vehicle the most.
3. In balanced braking cases,
  - (1) The speed of a vehicle influences its longitudinal and lateral changes more than the steering does, yet the steering of the vehicle is more dominant than the speed on heading changes.

- (2) Without the interaction of the steering, the front pair of wheel forces of a vehicle affects its lateral and heading changes greater than the rear pair of wheels, yet affects the longitudinal change more than the rear pair.

#### The effect of impact parameters

1. In oblique collision cases:
  - (1) Increasing the speed of the striking vehicle tends to increase the path length of the striking vehicle but to decrease the path length of the struck vehicle.
  - (2) Increasing the speed of the struck vehicle tends to increase the path length of the striking vehicle and the heading changes of both vehicles.
  - (3) Increasing the crush stiffness of the striking vehicle tends to increase the path length of the struck vehicle but to decrease the heading change of the struck vehicle.
  - (4) The crush stiffness of the struck vehicle has no significant influence on either the path length or heading change of both vehicles.
  - (5) Increasing the inter-vehicle friction tends to increase the heading change of the striking vehicle but has no other significant effect.
  - (6) The speed of the struck vehicle has the greatest influence on the path length and heading changes of the striking vehicle.

- (7) The crush stiffness of the striking vehicle affects the path length and heading changes of the struck vehicle more than does the crush stiffness of the struck vehicle.
2. In collinear collision cases:
- (1) Increasing the speed of the vehicle which has a smaller mass tends to decrease the path lengths of both vehicles but to increase the larger vehicle's heading change.
  - (2) Increasing the speed of the vehicle which has a larger mass tends to increase the path lengths as well as the heading changes of both vehicles.
  - (3) Increasing the crush stiffness of the smaller vehicle tends to increase its heading change.
  - (4) Increasing the crush stiffness of the larger vehicle tends to decrease the heading change of the smaller vehicle.
  - (5) Inter-vehicle friction has no significant effect on both vehicles in a collinear collision.
  - (6) The speed of the larger vehicle has the greatest effect on the path lengths of both vehicles.

### Model Implementation

Expert systems searching and converging techniques were reviewed and evaluated.

Blind searches did not meet the need for efficiency in this study. Directed searches like A\*

search were rejected because of the lack of information about the cost from a given node to the root node in the search space. Best-first search was rejected because it consumes more computer resources than the hill-climbing search.

The drawbacks of the hill-climbing search algorithm, such as foothill, plateau, and ridge problems, were minimized by conducting the same convergence with three different step widths, each smaller than the previous one, to minimize the chances of falling into any of the aforementioned draw-backs.

A blocked coordinate descending (BCD) convergence algorithm which was modified from a conventional hill-climbing search algorithm was developed and implemented. Seven BCD based converging engines were created in this study. Each was designed to conduct its own local optima based on the local optima converged by its preceding BCD converging task. These can be arranged in any order to meet a user's special needs in converging a simulation result on the final rest positions.

### Systematic Approach to Reconstructing a Traffic Accident

A systematic approach to reconstruct a typical two-car collision consists of the following ten steps:

- Step 1:        Locate the final rest position of each vehicle and record the coordinates. This includes the coordinates of each vehicle's center of mass, tires, and heading angle.
- Step 2:        Find the location of the collision. The location of the collision is critical to accident reconstruction. Usually the location of gouges,

scrapes, fluid, debris, the end of pre-impact skid marks, or the diversion of marks indicates where the collision occurred. However, sometimes none of the above were recorded by the investigator. We, then, need to run a simulation based on witness' statements to derive a possible colliding location.

- Step 3: Identify the type of marks between the final rest and colliding location. There are three different types of marks that a vehicle can leave on the pavement when it comes to a quick stop due to the friction of the pavement. Yaw marks indicate the vehicle was side sliding to a stop without braking. Scuff marks indicate the vehicle was rotating to a stop with either no or partial braking. Skid marks indicate the vehicle was sliding to a stop with its wheels fully locked up.
- Step 4: Calculate speeds for different mark types. When a vehicle leaves skid marks or scuff marks, the distance between the final rest and the colliding location must be measured. When yaw marks are left, the necessary measurements to calculate speed are the chord of the curve, and the middle ordinate of the chord.
- Step 5: Measure the departure angles for each vehicle.
- Step 6: Measure the impact angles for each vehicle.
- Step 7: Calculate the impact speed of each vehicle by using the conservation of linear momentum.

- Step 8: If pre-impact marks do not exist, go to step 10. If they do exist, mark types must be identified and speeds must be calculated, as in step 3 and 4. However, speeds obtained here are the speeds reduced before the collision.
- Step 9: The impact speed and pre-impact speed of each vehicle must be combined.
- Step 10: Generate the reconstruction report for this accident.

#### Systematic Approach to Conducting Accident Simulations

A traffic accident can be divided into three independent phases namely the pre-impact phase, impact phase and post-impact phase. This historical order of what was happening in the process of an accident can never be altered. This is the most important principle of designing a converging sequence for an accident case. For most general accident cases, the following order of converging tasks will produce a reasonable result:

- Step 1. Converging impact speeds. Impact speeds have a very significant effect on final rest position changes. Converging impact speeds first will reduce the number of iterations needed by the BCD converging tasks hereafter.
- Step 2. Converging wheel forces. Wheel forces affect impact speeds significantly. Thus, converging wheel forces right after impact speeds can fine tune the result of the impact speed convergence.

- Step 3. Converging collision angles. The collision angle convergence is part of the impact configuration convergence. It is more sensitive than the collision position convergence.
- Step 4. Converging collision positions. The collision position convergence is the second part of the impact configuration convergence.
- Step 5. Converging crush stiffness. The crush stiffness convergence is less sensitive than previous convergences but more sensitive than the inter-vehicle friction convergence on final rest positions.
- Step 6. Converging the inter-vehicle friction. The inter-vehicle friction only affects the heading change of the striking vehicle, hence, its convergence should be the last in the impact phase.
- Step 7. Converging post-impact steering. The heading angles of the front wheel planes could be changed by impact forces. Since this only has an effect at the separation stage in the process of an accident, it should always be the last converged.

### Recommendations

This study focused only on how to converge simulated final rest positions on RICSAC staged collisions. For real life accident cases, attention should be paid to the following while using this automatic coordinate converging system to come up with an accident scenario.

1. Converging engines developed in this study are designed for converging the inter-vehicle friction, crush stiffness, impact speed, wheel forces, angle of collision, position

of collision, and post-impact steering only. While there is a need for converging other contributing factors such as the center of gravity, weight, yaw movement of inertia, restitution, tire-ground friction, etc., of a vehicle, new converging engines should be created. The general control flow of converging engines can be used as a blueprint for designing new converging engines.

2. Converging sequences designed in this study were also specifically for RICSAC staged collisions. In real life, every accident is unique from other accident cases. For example, if evidence left at the scene strongly suggests where the maximum engagement occurred, the convergence of position of collision seems unnecessary. Therefore the position of collision convergence may be taken off the converging sequence. In other words, for every accident case, a reconstructionist should justify the converging sequence based on the quantity and quality of the information he/she obtained or derived from the physical evidence.
3. Even though the BCD algorithm and converging engines developed in this study improve the convergence of accident simulations very efficiently, a user should treat this automatic coordinate converging system as a decision-support tool rather than a solution for all accident cases. Since no computer system can replace human intelligence, a user should examine the result of the simulation convergence with his/her expertise and make sure that no laws of physics or engineering are violated.

APPENDIX A  
CORRELATION COEFFICIENTS OF DRIVER'S MANEUVERING BEHAVIOR  
PARAMETERS ANALYSIS

**Table A.1** Correlation Coefficients of Driver's Input and Coordinate Changes

	X Change	Y Change	H Change
SPEED	0.76410	0.24741	0.18126
STEER	-0.08970	0.23739	0.28162
F1	0.02769	0.08572	0.02696
F2	-0.03262	0.26210	0.49642
F3	0.07317	0.10221	-0.18071
F4	0.06020	0.24945	0.00730

**Table A.2** Correlation Coefficients of SPEED and Coordinate Changes at Different Wheel Forces Levels

Balanced Wheel Forces	SPEED		
	X Change	Y Change	H Change
0.00	0.73081	0.35960	0.22391
-0.20	0.75787	0.39404	0.20432
-0.40	0.79727	0.48015	0.30676
-0.60	0.81005	0.49561	0.30525
-0.80	0.83514	0.31157	0.15527
-1.00	0.83029	0.00000	0.03246

**Table A.3** Correlation Coefficients of STEER and Coordinate Changes at Different Wheel Forces Levels

Balanced Wheel Forces	STEER		
	X Change	Y Change	H Change
0.00	-0.29338	0.24479	0.61895
-0.20	-0.25708	0.29409	0.63729
-0.40	-0.15218	0.31874	0.63164
-0.60	-0.10981	0.32706	0.63216
-0.80	-0.00274	-0.26920	-0.31655
-1.00	0.00062	0.00000	-0.18611

**Table A.4** Correlation Coefficients of SPEED and Coordinate Changes at Different STEERS

STEER (deg)	SPEED		
	X Change	Y Change	H Change
0	0.71995	0.00000	0.00000
2	0.73913	0.27426	0.21270
4	0.76724	0.31975	0.27054
6	0.78601	0.31588	0.25885
8	0.79456	0.28957	0.22064
10	0.80134	0.29166	0.19687
12	0.80599	0.29328	0.17251

**Table A.5** Correlation Coefficients of F1 and Coordinate Changes at Different STEERs

STEER (deg)	F1		
	X Change	Y Change	H Change
2	0.05851	-0.33336	-0.32412
2	0.06457	0.00981	-0.07722
4	0.03980	0.13640	0.04858
6	0.01602	0.17820	0.10888
2	0.00254	0.20470	0.15236
10	-0.00392	0.20905	0.17426
12	-0.00606	0.21061	0.19295

**Table A.6** Correlation Coefficients of F2 and Coordinate Changes at Different STEERs

STEER (deg)	F2		
	X Change	Y Change	H Change
2	0.05851	0.33336	0.32412
2	-0.00544	0.41440	0.49946
4	-0.04512	0.30065	0.54342
6	-0.05880	0.23648	0.56511
2	-0.07054	0.24160	0.59380
10	-0.07366	0.22397	0.60659
12	-0.07576	0.21652	0.61540

**Table A.7** Correlation Coefficients of F3 and Coordinate Changes at Different STEERs

STEER (deg)	F3		
	X Change	Y Change	H Change
0	0.08881	-0.26133	-0.22959
2	0.10940	0.01364	-0.25544
4	0.09051	0.14679	-0.21625
6	0.06763	0.20101	-0.18008
8	0.05654	0.20058	-0.16331
10	0.04822	0.20709	-0.15104
12	0.04328	0.21161	-0.13996

**Table A.8** Correlation Coefficients of F4 and Coordinate Changes at Different STEERs

STEER (deg)	F4		
	X Change	Y Change	H Change
0	0.08881	0.26133	0.22959
2	0.06391	0.28085	0.06156
4	0.05749	0.25679	-0.02946
6	0.05752	0.25110	-0.06493
8	0.05495	0.25520	-0.06514
10	0.05117	0.26006	-0.06750
12	0.04806	0.26133	-0.06419

APPENDIX B  
CORRELATION COEFFICIENTS OF IMPACT PARAMETERS ANALYSIS

**Table B.1** Correlation Coefficients of Impact Parameters and Coordinate Changes in an Oblique Collision

	S1	S2	STIFF1	STIFF2	FRICTION
L1	0.47853	0.74819	-0.07907	-0.06199	-0.14178
L2	-0.29833	-0.00280	0.75975	-0.05450	-0.03525
DH1	0.02514	0.82170	0.06838	-0.04704	0.33798
DH2	0.16902	0.59767	-0.65986	-0.01617	-0.04210

**Table B.2** Correlation Coefficients of Impact Parameters and Coordinate Changes in a Collinear Collision

	S1	S2	STIFF1	STIFF2	FRICTION
L1	-0.40666	0.79503	0.16535	0.16972	-0.14337
L2	-0.44227	0.83698	-0.04656	-0.18989	0.09806
DH1	0.47761	0.47032	0.43050	-0.32266	0.08908
DH2	-0.05479	0.17305	0.17591	-0.02851	0.05110

# APPENDIX C OPTIMIZED INPUT DATA SETS FOR RICSAC CASES

1. Title? .....	RICSAC #1 Chevelle vs Pinto
2. Classes .....	4 2
3. Simulation time variables .....	0 4 .001 .01 .05 .1
4. Termination velocities .....	2 5
5. Initial positions .....	19.8 6.2 -30 -6.4 -2.7 90
6. Initial velocities .....	19.8 0 0 19.8 0 0
7. Vehicle #1 dimensions .....	54.7 59.2 61.8 98.8 114 77
8. Vehicle #1 inertias .....	4621 44739
9. Vehicle #2 dimensions .....	46.3 50.1 54.6 83.3 91.6 67.2
10. Vehicle #2 inertias .....	3082 23537.7
11. Steer angles .....	0 0
12. Vehicle #1 cornering stiffnesses ..	182.1 182.1 168.3 168.3
13. Vehicle #2 cornering stiffnesses ..	130.9 130.9 121 121
14. Tire-ground friction coef. ....	.87 0
15. Terrain boundary? .....	No
16. Boundary points .....	N/A
17. Secondary friction coef. ....	N/A
18. Stiffnesses .....	54 61
19. Sweep/depth intervals .....	2 .2 15
20. Friction factors .....	.47 5
21. Coefficients of restitution .....	.04606 .0017547 1.6711E-05

## WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time	Wheel forces (lb)				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.01	-0.01	-0.20	-0.20	0.730	0.00	0.00
					0.740	12.00	12.00

## WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time	Wheel forces (lb)				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.16	-0.01	-0.05	-0.20	0.730	0.00	0.00
					0.740	25.00	25.00

**Figure C.1** Input Data Set of Optimized RICSAC #1

1. Title?	RICSAC #2 Chevelle vs Pinto
2. Classes	4 2
3. Simulation time variables	0 4 .001 .01 .05 .1
4. Termination velocities	2 5
5. Initial positions	-10.6 8.4 -30 0.5 0.1 89
6. Initial velocities	33.5 0 0 27 0 0
7. Vehicle #1 dimensions	54.7 59.2 61.8 98.8 114 77
8. Vehicle #1 inertias	4621 44739
9. Vehicle #2 dimensions	46.3 50.1 54.6 83.3 91.6 67.2
10. Vehicle #2 inertias	3081 23530.1
11. Steer angles	0 0
12. Vehicle #1 cornering stiffnesses	182.1 182.1 168.3 168.3
13. Vehicle #2 cornering stiffnesses	130.9 130.9 121 121
14. Tire-ground friction coef.	.87 0
15. Terrain boundary?	No
16. Boundary points	N/A
17. Secondary friction coef.	N/A
18. Stiffnesses	51 59
19. Sweep/depth intervals	2 .2 15
20. Friction factors	.55 5
21. Coefficients of restitution	.04606 .0017547 1.6711E-05

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time	Wheel forces (lb)				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.36	-0.06	-0.20	-0.20			

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time	Wheel forces (lb)				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.07	-0.02	-0.22	-0.20	0.130	0.00	0.00
					0.140	-6.00	-6.00

**Figure C.2** Input Data Set of Optimized RICSAC #2

1. Title?	RICSAC Case No. 3, Torino vs Pinto
2. Classes	4 2
3. Simulation time variables	0 20 .001 .01 .05 .1
4. Termination velocities	2 5
5. Initial positions	-2.8 -0.3 0 12.2 1.9 1
6. Initial velocities	20.9 0 0 0.1 0 0
7. Vehicle #1 dimensions	54.7 59.2 61.8 98.8 114 77
8. Vehicle #1 inertias	4649 47914.6
9. Vehicle #2 dimensions	46.3 50.1 54.6 83.3 91.6 67.2
10. Vehicle #2 inertias	3120 23827.9
11. Steer angles	0 0
12. Vehicle #1 cornering stiffnesses	182.1 182.1 168.3 168.3
13. Vehicle #2 cornering stiffnesses	130.9 130.9 121 121
14. Tire-ground friction coef.	.87 0
15. Terrain boundary?	No
16. Boundary points	N/A
17. Secondary friction coef.	N/A
18. Stiffnesses	56 34
19. Sweep/depth intervals	2 .2 15
20. Friction factors	1.81 5
21. Coefficients of restitution	.04606 .0017547 1.6711E-05

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time	Wheel forces (lb)				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.01	-0.01	-0.09	-0.09	0.000	0.00	0.00

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time	Wheel forces (lb)				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.01	-0.01	-0.01	-0.18	0.000	0.00	0.00

**Figure C.3** Input Data Set of Optimized RICSAC #3

1. Title? ..... RICSAC Case No. 4, Torino vs Pinto
2. Classes ..... 4 2
3. Simulation time variables ..... 0 20 .001 .01 .05 .1
4. Termination velocities ..... 2 5
5. Initial positions ..... 2.8 -0.2 1 19.2 3.2 10
6. Initial velocities ..... 37.7 0 0 1.1 0 0
7. Vehicle #1 dimensions ..... 54.7 59.2 61.8 98.8 114 77
8. Vehicle #1 inertias ..... 4980 48214.8
9. Vehicle #2 dimensions ..... 46.3 50.1 54.6 83.3 91.6 67.2
10. Vehicle #2 inertias ..... 3130 24362.6
11. Steer angles ..... 0 0
12. Vehicle #1 cornering stiffnesses .. 182.1 182.1 168.3 168.3
13. Vehicle #2 cornering stiffnesses .. 130.9 130.9 121 121
14. Tire-ground friction coef. .... .87 0
15. Terrain boundary? ..... No
16. Boundary points ..... N/A
17. Secondary friction coef. .... N/A
18. Stiffnesses ..... 51 59
19. Sweep/depth intervals ..... 2 .2 15
20. Friction factors ..... .55 5
21. Coefficients of restitution ..... .04606 .0017547 1.6711E-05

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time (sec.)	----- Wheel forces (lb) -----				Time - Steer Angles -		
	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.11	-0.21	-0.20	-0.20	0.200	0.00	0.00
					0.210	17.00	17.00

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time (sec.)	----- Wheel forces (lb) -----				Time - Steer Angles -		
	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.01	-0.01	-0.25	-0.69	0.000	0.00	0.00

**Figure C.4** Input Data Set of Optimized RICSAC #4

1. Title? .....	RICSAC Case No. 6, Chevelle vs Rabbit
2. Classes .....	4 2
3. Simulation time variables .....	0 20 .001 .01 .05 .1
4. Termination velocities .....	2 5
5. Initial positions .....	5 -2.9 0 16.6 -0.7 120
6. Initial velocities .....	21.5 0 0 21.5 0 0
7. Vehicle #1 dimensions .....	54.7 59.2 61.8 98.8 114 77
8. Vehicle #1 inertias .....	4300 41631.2
9. Vehicle #2 dimensions .....	46.3 50.1 54.6 83.3 91.6 67.2
10. Vehicle #2 inertias .....	2623 20032.3
11. Steer angles .....	0 0
12. Vehicle #1 cornering stiffnesses ..	182.1 182.1 168.3 168.3
13. Vehicle #2 cornering stiffnesses ..	130.9 130.9 121 121
14. Tire-ground friction coef. ....	.87 0
15. Terrain boundary? .....	No
16. Boundary points .....	N/A
17. Secondary friction coef. ....	N/A
18. Stiffnesses .....	52 70
19. Sweep/depth intervals .....	2 .2 15
20. Friction factors .....	.69 5
21. Coefficients of restitution .....	.04606 .0017547 1.6711E-05

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time	Wheel forces (lb) -----				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.01	-0.02	-0.20	-0.20	0.000	0.00	0.00

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time	Wheel forces (lb) -----				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.40	-0.01	-0.50	-0.20	0.000	0.00	0.00

**Figure C.5** Input Data Set of Optimized RICSAC #6

1. Title?	RICSAC Case No. 7, Chevelle vs Rabbit
2. Classes	4 2
3. Simulation time variables	0 20 .001 .01 .05 .1
4. Termination velocities	2 5
5. Initial positions	3.3 -1 0 16.9 -0.5 105
6. Initial velocities	21.1 0 0 22 0 0
7. Vehicle #1 dimensions	54.7 59.2 61.8 98.8 114 77
8. Vehicle #1 inertias	3700 35822.2
9. Vehicle #2 dimensions	46.3 50.1 54.6 83.3 91.6 67.2
10. Vehicle #2 inertias	1700 12983.2
11. Steer angles	0 0
12. Vehicle #1 cornering stiffnesses	182.1 182.1 168.3 168.3
13. Vehicle #2 cornering stiffnesses	130.9 130.9 121 121
14. Tire-ground friction coef.	.87 0
15. Terrain boundary?	No
16. Boundary points	N/A
17. Secondary friction coef	N/A
18. Stiffnesses	62 45
19. Sweep/depth intervals	2 .2 15
20. Friction factors	.56 5
21. Coefficients of restitution	.04606 .0017547 1.6711E-05

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time	Wheel forces (lb)				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.03	-0.01	-0.20	-0.20	0.000	0.00	0.00

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time	Wheel forces (lb)				Time	Steer Angles -	
(sec.)	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.29	-0.01	-1.19	-0.20	0.000	0.00	0.00

**Figure C.6** Input Data Set of Optimized RICSAC #7

1. Title? ..... RICSAC Case No. 8 Chevelle vs Chevelle
2. Classes ..... 4 4
3. Simulation time variables ..... 0 4 .001 .01 .05 .1
4. Termination velocities ..... 2 5
5. Initial positions ..... -10.6 3 2 -0.2 1.7 91
6. Initial velocities ..... 20.9 0 0 20.7 0 0
7. Vehicle #1 dimensions ..... 54.7 59.2 61.8 98.8 114 77
8. Vehicle #1 inertias ..... 4479 43364.2
9. Vehicle #2 dimensions ..... 54.7 59.2 61.8 98.8 114 77
10. Vehicle #2 inertias ..... 4710 45600.7
11. Steer angles ..... 0 0
12. Vehicle #1 cornering stiffnesses .. 182.1 182.1 168.3 168.3
13. Vehicle #2 cornering stiffnesses .. 182.1 182.1 168.3 168.3
14. Tire-ground friction coef. .... .87 0
15. Terrain boundary? ..... No
16. Boundary points ..... N/A
17. Secondary friction coef ..... N/A
18. Stiffnesses ..... 21 26
19. Sweep/depth intervals ..... 2 .2 15
20. Friction factors ..... .56 5
21. Coefficients of restitution ..... .04606 .0017547 1.6711E-05

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time (sec.)	----- Wheel forces (lb) -----				Time - Steer Angles -		
	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.82	-0.01	-0.20	-0.20	0.140	0.00	0.00
					0.150	1.00	1.00

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time (sec.)	----- Wheel forces (lb) -----				Time - Steer Angles -		
	R/F	L/F	R/R	L/R	(Sec.)	R/F	L/F
0.000	-0.86	-0.01	-0.10	-0.20	0.140	0.00	0.00
					0.150	22.00	22.00

**Figure C.7** Input Data Set of Optimized RICSAC #8

1. Title?	RICSAC #9 Honda vs Torino
2. Classes	1 4
3. Simulation time variables	0 20 .001 .01 .05 .1
4. Termination velocities	2 5
5. Initial positions	0 0 0 8.5 -5.9 90
6. Initial velocities	20.7 0 0 22.1 0 0
7. Vehicle #1 dimensions	45.1 48.1 51.1 76 83.8 60.8
8. Vehicle #1 inertias	2256 11712
9. Vehicle #2 dimensions	54.7 59.2 61.8 98.8 114 77
10. Vehicle #2 inertias	4900 47440.2
11. Steer angles	0 0
12. Vehicle #1 cornering stiffnesses	93.8 93.8 87.9 87.9
13. Vehicle #2 cornering stiffnesses	182.1 182.1 168.3 168.3
14. Tire-ground friction coef.	.87 0
15. Terrain boundary?	No
16. Boundary points	N/A
17. Secondary friction coef.	N/A
18. Stiffnesses	45 15
19. Sweep/depth intervals	2 .2 15
20. Friction factors	.79 5
21. Coefficients of restitution	.04606 .0017547 1.6711E-05

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time (sec.)	----- Wheel forces (lb) -----				Time (Sec.)	- Steer Angles -	
	R/F	L/F	R/R	L/R		R/F	L/F
0.000	-0.30	-0.10	-0.01	-0.01			

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time (sec.)	----- Wheel forces (lb) -----				Time (Sec.)	- Steer Angles -	
	R/F	L/F	R/R	L/R		R/F	L/F
0.000	-0.30	-0.01	-0.30	-0.20	0.610	0.00	0.00
					0.620	15.00	15.00

**Figure C.8** Input Data Set of Optimized RICSAC #9

1. Title?	RICSAC Case No. 11, Vega vs Torino
2. Classes	2 4
3. Simulation time variables	0 4 .001 .01 .05 .1
4. Termination velocities	2 5
5. Initial positions	16.1 -3.9 172 0.2 0 0
6. Initial velocities	21.4 0 0 21.2 0 0
7. Vehicle #1 dimensions	46.3 50.1 54.6 83.3 91.6 67.2
8. Vehicle #1 inertias	3041 23224.6
9. Vehicle #2 dimensions	54.7 59.2 61.8 98.8 114 77
10. Vehicle #2 inertias	4850 46956.1
11. Steer angles	0 0
12. Vehicle #1 cornering stiffnesses	130.9 130.9 121 121
13. Vehicle #2 cornering stiffnesses	182.1 182.1 168.3 168.3
14. Tire-ground friction coef.	.87 0
15. Terrain boundary?	No
16. Boundary points	N/A
17. Secondary friction coef.	N/A
18. Stiffnesses	44 61
19. Sweep/depth intervals	2 .2 15
20. Friction factors	.55 5
21. Coefficients of restitution	.04606 .0017547 1.6711E-05

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time (sec.)	----- Wheel forces (lb) -----				Time (Sec.)	- Steer Angles -	
	R/F	L/F	R/R	L/R		R/F	L/F
0.000	-0.01	-0.01	-0.20	-0.20	0.730	0.00	0.00
					0.740	12.00	12.00

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time (sec.)	----- Wheel forces (lb) -----				Time (Sec.)	- Steer Angles -	
	R/F	L/F	R/R	L/R		R/F	L/F
0.000	-0.16	-0.01	-0.05	-0.20	0.730	0.00	0.00
					0.740	25.00	25.00

**Figure C.9** Input Data Set of Optimized RICSAC #11

1. Title?	RICSAC #12 Vega vs Torino
2. Classes	2 4
3. Simulation time variables	0 4 .001 .01 .05 .1
4. Termination velocities	2 5
5. Initial positions	15.6 -2.3 171 -0.1 1.7 0
6. Initial velocities	27.8 0 0 25.8 0 0
7. Vehicle #1 dimensions	46.3 50.1 54.6 83.3 91.6 67.2
8. Vehicle #1 inertias	3130 23904.3
9. Vehicle #2 dimensions	54.7 59.2 61.8 98.8 114 77
10. Vehicle #2 inertias	4512 43683.7
11. Steer angles	0 0
12. Vehicle #1 cornering stiffnesses	130.9 130.9 121 121
13. Vehicle #2 cornering stiffnesses	182.1 182.1 168.3 168.3
14. Tire-ground friction coef.	.87 0
15. Terrain boundary?	No
16. Boundary points	N/A
17. Secondary friction coef.	N/A
18. Stiffnesses	59 51
19. Sweep/depth intervals	2 .2 15
20. Friction factors	.55 5
21. Coefficients of restitution	.04606 .0017547 1.6711E-05

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 1

Time (sec.)	----- Wheel forces (lb) -----				Time - Steer Angles - (Sec.)	R/F L/F	
	R/F	L/F	R/R	L/R		R/F	L/F
0.000	-0.01	-0.02	-0.20	-0.20	0.140	0.00	0.00
					0.150	31.00	31.00

#### WHEEL FORCE AND STEER TABLE - Vehicle No. 2

Time (sec.)	----- Wheel forces (lb) -----				Time - Steer Angles - (Sec.)	R/F L/F	
	R/F	L/F	R/R	L/R		R/F	L/F
0.000	-0.02	-0.03	-0.20	-0.20	0.140	0.00	0.00
					0.150	-2.00	-2.00

**Figure C.10** Input Data Set of Optimized RICSAC #12

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## BIOGRAPHICAL SKETCH

Yue-jeh Cheng was born in Penhu, Taiwan, Republic of China, on January 7, 1957. At the age of three, his family moved from Penhu to Ilan and from Ilan to Taipei again at his age of seven. He then attended public school and graduated from National Normal University Affiliated High School in Taipei, in June, 1976.


In August, 1976, he enrolled at Central Police College, now Central Police University, where he studied traffic control and communications and received the Bachelor of Science degree in June, 1980. Unlike most of his schoolmates, who served in the police force, Mr. Cheng served as an assistant instructor at Central Police College.

He continued his studies in traffic engineering sciences at Central Police College in August, 1985, and was awarded the Master of Science in June, 1987. Following graduation, Mr. Cheng served as an instructor teaching traffic police and computer sciences related courses at Central Police College for four years before he came to the U.S. to pursue his Ph.D.


I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

  
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